AN ANALYSIS OF STRATEGIES OF MEASUREMENT OF 3D ROTARY ELEMENTS

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Abstract

Measurements of form deviations of 3D elements can be conducted with the use of various strategies, differing in a number and distribution of sampling points located on an investigated surface. Low number of sampling points or measured sections can lead to the situation that some surface irregularities are not detected by a measuring system. An application of higher density of sampling points, in turn, results in significant lengthening of measurement time, which is undesirable, if one takes into account requirements of modern manufacturing processes. The main goal of this paper is to analyze major advantages and drawbacks of measurement strategies of 3D rotary elements that are described in the scientific literature. Additionally, the concept of a novel, adaptive measurement strategy is presented.

Keywords: form deviation; measurement strategy; rotary elements; uniform sampling; adaptive strategy

1. Introduction

Rotary element are significant and numerous group of machine parts. They are used in a number of branches of engineering industry, including bearing industry (components of rolling bearings) [1], automotive industry (shafts, engine pistons and cylinders), metallurgy (metallurgical cylinders), ship industry (drive shafts) and many more [2]. In industrial practice measurements of form deviations of such elements is simplified – usually roundness measurement is conducted in one or a few preselected cross-sections of investigated part.

Measurements of 3D parameters are practically limited to the problem of evaluation of cylindricity, which is performed with the use of special-purpose radial systems for measurements of roundness and cylindricity deviations (for example series of Talyrond instruments by Taylor Hobson). If tolerances of parts permit, such measurements are conducted with the use of coordinate measuring machines, too. Considering the problem of correct measurement of form deviations of 3D elements it is noteworthy that a very important issue is to apply relevant measuring strategy, i.e. scanning trajectory, which is basically a path along which the sensor moves on the surface to be measured. Selection appropriate measuring strategy is a matter of great importance and refers to the problem of obtaining satisfying measurement accuracy and measurement time. The aim of this paper is to discuss major advantages and limitations of the strategies described in the literature. In addition, outlines of the new strategy proposed by authors is discussed.

2. Strategies used to measure form deviations of 3D elements

An analysis of the problem of cylindricity measurements shows that there are three main groups of measuring strategies. The first group are uniform sampling strategies that are most common strategies usually applied in industrial practice. The second group constitute strategies fitted to measured surface on the basis of predicted pattern of irregularities. The last group of the strategies that are described in the literature are so-called adaptive strategies.

As it was previously mentioned, at present time the most popular are uniform sampling strategies. However, due to the efforts aiming at shortening measurement time intensive research work is conducted that is focused on applying adaptive strategies. These are relatively novel concepts and they are still under study by a number of scientists dealing with metrology of geometrical quantities.

2.1 Uniform sampling strategies

Standard ISO 12180 describes following uniform sampling strategies used to measure cylindricity: cross-sections, strategy, longitudinal sections strategy, 'bird-cage' strategy and single points strategy. Apart from mentioned above, also helical trace strategy is quite often applied in industry. The strategies are shown in Fig. 1.

Fig. 1. Strategies used to measure cylindricity deviations: a) single points strategy, b) longitudinal sections strategy, c) cross-sections strategy, d) "bird-cage" strategy, e) helical trace strategy [3].

Usually measurements of cylindricity deviations are performed with the use of the cross-sections strategy and the longitudinal sections strategy. Single points strategy is less common as the limited number of sampling points allows a rough evaluation of form deviations only. The strategy that permits the most accurate measurement is the "bird-cage" strategy. However, due to computational problems this strategy has not been available in the software of measuring systems for a long time. At the moment, there are new measuring systems that allow application this strategy. The most important advantage of the "bird-cage" strategy is that it permits dense covering of measured surface with a grid of sampling points. Therefore such results are most reliable. The major drawback of the "bird-cage" strategy is that it is very time consuming. Thus, its application under industrial conditions is limited. The strategy that was not described in the standard ISO 12180 is the helical trace strategy. This strategy is a compromise solution between the strategies of cross-sections and longitudinal sections and it is quite often applied under industrial conditions.

In general, it should be noted that the strategies shown in Fig. 1 allow uniform sampling. It means that the whole surface of the specimen is scanned in the same way. Thus, for the case of cross-section, longitudinal section and "bird-cage" strategy all the linear distance between all cross-sections and angular distance between longitudinal sections is the same. The spiral trace strategy can be regarded as a uniform sampling strategy, too since the parameter that describes sampling density, which is pitch angle, remains constant during the measurement. Application of the single points strategies also requires approximate uniform distribution of sampling points on the surface under investigation. It can be performed with the use of specific numerical methods, for example by applying so-called Hammersley sequence.

Uniform sampling strategies are very useful if surfaces under study are characterized by regular pattern of form errors. However, sometimes significant irregularities are located only in a certain area of the surface. Such area should be then sampled with the use of many more points than other part of the surface. This is the reason why a research activities are conducted that are focused on development of a strategy that would denser sampling in areas where significant surface defects are predicted.

2.2 Strategies to be fitted to predicted form errors pattern

These strategies are fitted to the surface under study on the basis of predicted distribution of surface irregularities. If we have information about the machining process of the surface, then we can predict most probable distribution of the irregularities of the surface. For example, cylindrical surface of workpieces machined by turning that were placed in a three-jaw chucks are very often characterized by a triangular error (i.e. the third harmonic component is dominant if we conduct its spectral analysis). Additionally, workpieces that were placed in lathe centers are usually characterized by a saddle-shaped error.

Fig. 2. Strategies of form error measurement of saddle-shaped element: on the left – the strategy applied usually – not fitted to the predicted form error of the part; on the right – the strategy designed on the basis of predicted form error of the element [4].

Strategies fitted to predicted model of irregularities can be designed on the basis of data of preliminary measurements or on the basis of assumed pattern of form errors. An example of the former approach is a method of harmonics fitting described in work [5]. This method applies statistical evaluation of characteristics of individual Fourier components of the profile in order to establish as small set of sampling points data as possible that allows reliable evaluation of form errors of the surface under study.

The latter approach is given in work [6]. In this method, a preliminary model of the shape of the surface is assumed. The model is described mathematically by the linear combination of the set of base functions (for example, polynomials, Fourier components or eigenfunctions). The model is then used to design the grid of sampling points. After the measurement on the basis of the values in preselected sampling points coefficients of assumed model of the linear combination are calculated (taking into account uncertainty of fitting). The coefficients are then used to reconstruct the image of the whole surface under study.

2.3 Adaptive strategies

Adaptive strategies are iterative ones. In the case of application of adaptive strategies, the sampling is conducted in a few stages. The first stage is a preliminary measurement. The preliminary measurement is usually performed with the use of uniform sampling. After the preliminary measurement Next, on the basis of obtained measurement data, a relevant algorithm is applied to find the areas where the risk of occurring of large local disturbances is high. After conducting measurements in these areas the value of presumed coefficient is calculated.

The value of this coefficient indicates if the measurements should be finished or it is necessary to conduct the next series of measurements applying denser sampling. Such approach uses so-called Kriging models quite often. The name of the method comes from the name South African engineer who has the first researcher to apply this method to predict changes of the signal in geostatics in the sixties of the XX. century.

At present, these models are more and more common to predict localization of subsequent sampling points. In Kriging models the signal is modified with the use of the set of base functions and their coefficients supplemented by a random component whose expected value is equal to zero and for whom the covariance between the input and output remains constant. Fig. 3 shows an algorithm that presents an application of Kriging model to evaluate form deviations by an adaptive strategy proposed in work [7].

Fig. 3. Block diagram showing an example of the application of Kriging model to evaluate form deviations of elements [7]

2.4 An approach to adaptive strategy proposed by authors

Taking into account limitations of the strategies presented above authors have developed a novel concept of applying the adaptive strategy to evaluate form deviations of 3D rotary elements. The strategy is to be applied with the use of coordinate measuring machines [8, 9].

The strategy consists of two stages: the former is a preliminary measurement and the latter are additional measurements. Preliminary measurement will be conducted along preselected scanning path. Authors propose to apply following uniform sampling strategies for the preliminary measurement: helical trace strategy, cross-sections strategy and longitudinal sections strategy. Let us assume that we conduct preliminary measurement by the helical trace strategy. If measurement results show that in a certain area of the surface occurs a large change of the signal, then we conduct additional measurements, performed for example in the cross-section and the longitudinal section lying in analyzed fragment of the surface. Additionally, we can also carry out a new measurement along the helical trace applying lower value of the pitch angle, which will contribute to denser covering the surface with the grid of sampling points. For the preliminary measurements with the use of cross-section and longitudinal sections strategy the procedure can be as follows: we calculate correlation coefficients between neighboring profiles. If the value of the coefficient is lower than presumed permitted value then we conduct additional measurements in the area between these profiles.

3. Conclusions

Strategies based on predicted model of irregularities and adaptive strategies described in the section 2.2 and 2.3. are still under investigation and they have not been widely applied under industrial conditions. They have lots of advantages, however also severe drawbacks. The strategy based on predicted model of irregularities allows accurate sampling only in preselected areas. However, real technological processes are disturbed by many random factors that can contribute to arising irregularities in areas different from those that were predicted before the process initialization (in particular if the process becomes statistically unregulated). Referring to the problem of adaptive strategies described in section 2.3 it should be noted that these are iterative methods, thus they are quite complex computationally. Moreover, their application with the use of coordinate measuring machine can be troublesome as there is a risk of the collision of the measuring tip with the surface of the specimen. The risk results from the fact that sampling points can be generally different for elements whose nominal dimensions are the same.

In addition, it is noteworthy that at present time form deviations are usually measured by coordinate measuring machines equipped with scanning probe heads. Such probe heads allow obtaining very dense sampling in a relatively short time. Thus, methods for whom areas requiring denser sampling are to be calculated become out-of-date very quickly. These methods are still relevant if touch-triggering probe heads are used but such type of probe heads is dynamically replaced with scanning ones at present time.

The concept of two-stage adaptive strategy of measurements of 3D machine parts seems to be interesting from the technological point of view. Such strategy will allow obtaining accurate information about surfaces under study and will be less time-consuming than other adaptive sampling strategies. However, in order to evaluate the applicability of this strategy under industrial conditions it will be necessary to conduct a series of experiments, which is planned in the nearest future.

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