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RESEARCH ON ACCURATE IN SITU MEASUREMENTS OF CYLINDRICITY

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Abstract − In many industries (for example, in paper, electric or ship industry), large and heavy cylindrical elements play very important role. Such workpieces should posses very good quality of form and dimensions. Sometimes, they may be deformed under certain operating conditions, e.g. due to a high temperature or great external or internal loads. Consequently, wear and damage of the working surfaces are observed. Therefore cylindricity deviations of such workpieces should be measured during their manufacturing and exploitation. However, some of the workpieces cannot be measured accurately by existing measuring instruments because they are too large or too heavy and therefore they cannot be placed on the measuring table of the instrument. This is why the industries manufacturing or applying cylinders expect that measurements of cylindricity profiles will be made directly on the machine tool or in the work area. In the paper methods allowing such measurements are investigated. The methods are divided into two main groups: multisensor and V-block methods. Most important advantages and disadvantages of both groups of methods allowing accurate in situ cylindricity measurements are given as conclusions.

Keywords: cylindricity, deviation, in situ measurement

1. INTRODUCTION

Parameters and recommendations relating to cylindricity measurements are described in standards ISO 12180 – 1,2. This standard is a link of the chain of GPS standards (where GPS stands for *Geometrical Product Specification*). According to standard ISO/DIS 12180-1, an entire cylindricity deviation can be regarded as a superposition of three types of deviations: a straightness deviation of the cylinder axis, a form deviation in the longitudinal section of the cylinder, and a form deviation in the cross-section of the cylinder. Therefore accurate measurement of cylindricity requires employing specialized measuring instruments.

The knowledge of the measurement of cylindricity profiles is relatively limited. The works available on the subject mainly concern the application of radius change methods. The radius change methods can be divided into two main groups: ones employing a rotary sensor, and ones employing a rotary table (see Fig. 1).

The radius change measurements of cylindricity profiles are of a high metrological level. Characterised by high accuracy, they provide complete information of the analysed surface. However, the radius change measuring instruments are applied only if it is possible to place the workpiece on the measuring table.

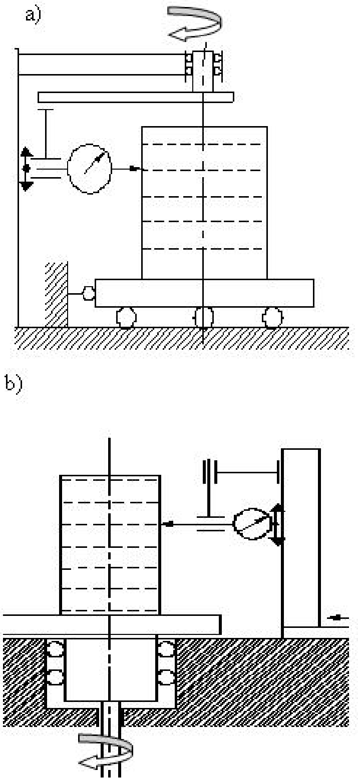

Fig. 1. Radius change cylindricity measurements: a) using the rotary sensor; b) using the rotary table

In many industries (for example, in paper, electric or ship industry), large and heavy cylindrical elements play very important role. Such workpieces should posses very good quality of form and dimensions. Sometimes, they may be deformed under certain operating conditions, e.g. due to a high temperature or great external or internal loads. Consequently, wear and damage of the working surfaces are observed. Therefore cylindricity deviations of such workpieces should be measured during their manufacturing

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and exploitation. However, some of the workpieces cannot be measured accurately by existing measuring instruments because they are too large or too heavy and therefore they cannot be placed on the measuring table of the instrument. This is why the industries manufacturing or applying cylinders expect that measurements of cylindricity profiles will be made directly on the machine tool or in the work area.

2. METHODS ALLOWING ACCURATE IN SITU CYLINDRICITY MEASUREMENTS

As it was previously mentioned, radius change methods (called also radial or non-reference methods) are usually applied to accurate cylindricity measurements. These methods require placing the workpiece on the measuring table of the instrument. Therefore, they do not allow performing in situ measurements. This is the reason why numerous R&D teams make intensive efforts on development of methods allowing accurate in situ cylindricity measurements.

2.1. Multi-sensor methods

Most methods allowing in-process cylindricity measurements require employing the set of measuring sensors. These methods are usually based on so-called error separation technique (EST). They usually employ elements of the machine tool on which the workpiece is placed as components of the measuring system (for example guideways of the machine tool are used as the guideways of measuring sensors, etc.).

The most popular approach in such methods is dividing the cylindricity measurement into roundness measurements in subsequent cross-sections of the workpiece and straightness measurements along the generatrix of the cylinder. Usually, roundness measurement is carried out by so-called three-point method using three measuring sensors that are located in one plane and they are aligned in relation to each other at clearly defined angles. The scheme of classical 3-point measuring system is shown in Fig. 2.

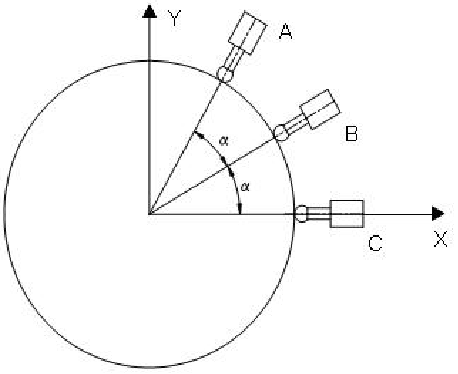

Fig. 2. Roundness measurement by three sensors: A, B and C (the three-point method) [1]

In the 3-point method, three measuring sensors (denoted in Fig. 2 as A, B and C) are fixed around the workpiece to detect roundness profile and two-dimensional spindle error components simultaneously. They scan surface while the workpiece is rotating.

The effect of the spindle error is canceled in the differential output of the probes and the correct roundness profile can be evaluated from the differential data. It can be done, for example, by integration or DFFT method [2].

Straightness measurement, in turn, is usually performed by so-called sequential two-point method (see Fig. 3).

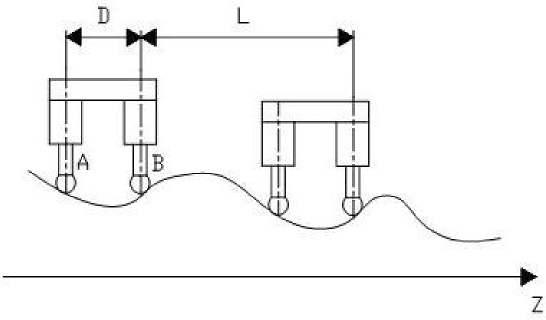

Fig. 3. Straightness measurement by the sequential two-point method [1]

In the sequential two-point method the system of two sensors (A and B) measures the straightness profile. Knowing the distance between the sensors *D* and the displacement of the system of sensors *L* one can calculate and remove the influence of the Z directional error.

The method allowing in situ cylindricity measurements and combining the concept of two- and three-point method is the method described by T. R. Nyberg in [3]. In the concept presented by Nyberg the system of four measuring sensors is placed on the tool carriage of the turning machine tool (see Fig. 4).

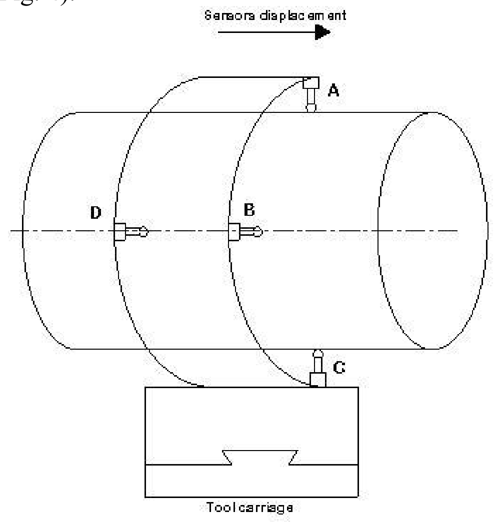

Fig. 4. The system of measuring sensors described by Nyberg

In Nyberg's method signals from sensors A, B and C are used for calculation of the out-of-roundness (3-point method) and the out-of-straightness is calculated on the basis of the signals from the sensor B and D (2-point method). So, the signal from the sensor B is used twice. The method developed by Nyberg was successfully verified experimentally on the measuring device that was designed and constructed according to the assumptions of Nyberg's concept.

2.2. V-block cylindricity measurement

Among described concepts of in situ cylindricity measurements method presented for example in [4] seems to be quite interesting and original (see Fig. 5).

The concept of cylindricity measurement by means of the V-block method assumes that the measured object is placed on a machine tool. Two interconnected V-blocks adhere to its surface. The connecting element of the V-block functions additionally as a guide, along which a measuring sensor is shifted. In the measuring device, both the object's angle of rotation and the sensor's displacement are controlled by means of a computer controller. The cylindricity measurement of an object implies appropriate scanning of the object's surface with a measuring sensor, along the suitably designed trajectory, through appropriate steering of the object's angle of rotation and sensor's displacement. Values α and β shown in Fig. 5 are the angular parameters of the V-block method for cylindricity measurement. They are responsible for detecting particular harmonic components of the measured cylindricity profile.

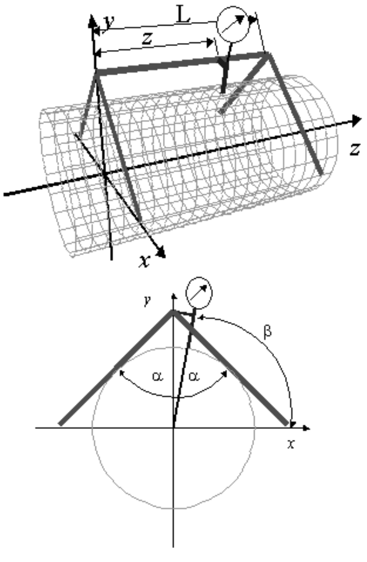

Fig. 5. Cylindricity measurement using V-block method

The developed concept requires a mathematical transformation of the sensor-recorded profile into the real profile.

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 a profile and the surface of the nominal cylinder is equal to $R(\varphi,z)$, where φ and z are 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 a profile from the surface of the nominal cylinder. In the reference method distance of the profile at the point of contact with the sensor from the nominal cylinder is equal to:

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

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. We know that the points of contact of the workpiece and one of the supports coincide with the points of contact of the supports and the nominal cylinder, so the distance of the profile from the nominal cylinder at the point of contact of the workpiece and the supports is equal to zero. By using this knowledge and by expanding of the profile in a complex Fourier series we can derive equations , that we can use to calculate the real profile R on the basis of measured profile F. Let $\hat{F}_{nz}$ and $\hat{R}_{nz}$ be the n-th components of the expansion of the profiles $F(\varphi,z)$ and $R(\varphi,z)$ in a complex Fourier series $n=-\infty,\dots,-1,0,1,\dots,\infty$. The the dependencies useful for transformation of meaured profile into the real profile we can define as follows:

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

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

Harmonic components $\hat{R}_{n0}$ and $\hat{R}_{nL}$ in the first and the last cross section at z coordinate equal to *0* and L, respectively) we can determine from following equations

$$\hat{F}_{n0} = \hat{R}_{n0}\hat{K}_n; \tag{4}$$

$$\hat{F}_{nL} = \hat{R}_{nL}\hat{K}_n \tag{5}$$

where $\hat{K}_n = e^{in\beta} - \hat{M}_n$

K_n is the so-called coefficient of detectability. Equations (1)-(5) constitute the complete mathematical model for precise calculation of the constant value of a deviation of the nominal cylinder.

Described method was successfully verified theoretically (by computer simulations) and experimentally (by statistical tests carried out using special test measuring stand). The results of the verification can be found in [4]. The test measuring stand for V-block cylindricity measurements os shown in Fig. 6.

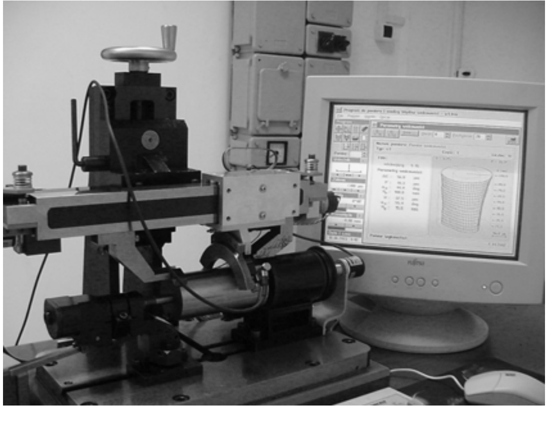

Fig. 6. Test measuring stand for V-block cylindricity measurements

3. COMPARISON OF MULTISENSOR AND V-BLOCK METHOD

An analysis of the multisensor and V-block method of cylindricity measurements makes it possible to distinguish some characteristic features of above mentioned measuring methods.

Following characteristic features of the multisensor methods can be distinguished:

- the workpiece is measured by the system of sensors (three sensors are necessary to cancel the spindle error and two sensors are necessary to cancel the axial error),
- detection of harmonic components of roundness profiles depends on location of sensors in relation to the workpiece,
- the method is well recognized and described mathematically,
- the method is applied in practice,
- multisensor measuring systems are usually attached to concrete machine tool.

Analyzing the V-block method of cylindricity measurement one can come to following conclusions:

- workpiece is measured by the system consisting of two connected V-blocks and one measuring sensor,
- the measuring signal is not influenced by spindle and axial errors,
- detection of the harmonic components of roundness profiles depends on the angle of V-blocks and location of the sensor,
- the method is well described mathematically,
- the concept was successfully verified in practice using the test measuring stand.
- the main assumption of the method is that the measuring system is mobile (it should not be attached to the concrete machine tool).

Taking to account conclusions given above we can say that:

- both methods are very interesting and each of them allows accurate in-situ cylindricity measurement.
- both methods have similar disadvantage – they cannot detect all harmonic components of the roundness profile,
- the multisensor method is more often applied in practice, there are numerous measuring devices that are based on this concept, presented V-block method was verified in practice only using the test measuring device.
- in the multisensor method spindle and axis error are identified and canceled, in the V-block method spindle and axis error do not influence measurement result.
- multisensor measuring devices are usually attached to the specific machine tool, the device based on the V-block method is mobile, therefore it is much more universal.

4. CONCLUSIONS

Nowadays the most popular methods of accurate cylindricity measurements are radius change methods. They are of a high metrological level and they provide accurate information of the analysed surface. However, devices based on the radius change method are applied only for workpieces that can be placed on the measuring table. However, in numerous branches of industry (for example, in paper, electric or ship industry), large and heavy cylindrical elements play very important role. Such elements cannot be placed on the measuring table of the instrument because of their significant size and weight. Therefore industries manufacturing or applying cylinders expect methods allowing accurate in-situ cylindricity measurements.

Most concepts of accurate in-situ cylindricity measurements are based on combining the three-point (for roundness measurements) and two-point method (for straightness measurements). Such approach is quite well described and resulted in development of measuring systems allowing accurate on-machine cylindricity measurements.

Other approach is the concept proposed by authors. In this concept the measuring system consists of two connected V-blocks and the measuring sensor that moves along the element connecting the V-blocks. The advantage of this method is the fact that spindle errors do not influence the measurement result. Moreover, proposed system is mobile. Therefore the measurement could be performed not only on a specific machine tool during the manufacturing of the workpiece but also during its exploitation. Taking to account requirements of numerous branches of industry (for example paper, steel or shipping industry) it is a very significant advantage of proposed method.

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