A method for the measurement of the diameters of large-scaled shafts

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Abstract. This article discusses a method for the measurement of the root-mean-square circles of the important cylindrical surfaces of large-scale shafts. The method allows the realization of the measurement directly on the machine by the use of the results of measuring the radial runout of the relevant cross-sections of the shaft and of one attached to the shaft forehead etalon ring which has pre-calibrated both the diameter and as well as its roundness deviation. The main sources of uncertainty have been analysed.

Key words: large shafts, measurement of diameters, uncertainty.

1. Introduction

High requirements are demanded for the geometric accuracy of the surfaces of rotation of the large-scaled shafts in the transport and heavy machinery industry, as well as the power industry and other industries, such as turbine, roller, crankshaft, etc. Tolerances of such diameters are usually within 15-60 μm.

The large sizes and weight of these objects (diameters up to 1500 mm, length up to 20000 mm and weight up to 80-100 t) specify the measurement of such tolerances.

The most widely used measurement methods by the means of mechanical measuring instruments (like micrometres) do not assure the necessary accuracy. The application of coordinate measuring machines (CMM) is highly restricted by shape of the shafts and also their positioning in the machines working space as well as economic reasons make their use impossible [4].

Indirect method of measurement using measurement data by the circle elements or by contact rollers also do not give the required accuracy, which in turn is highly influenced by the measured cross sections form deviations.

Furthermore, these methods give information only for some average value of these diameters [3].

The main goal of this paper is a new method of the measurement of the diameters of large-scaled shafts developed by the authors that assures high measurement accuracy directly on the production machine [2].

2. Description of the method

2.1. Essentials of the measurement

The principle of the operation during the positioning of the shaft on the machine centres is shown in Fig. 1.
A ring with a calibrated diameter is attached to the one of the shaft faces. The diameter of the ring also its form deviation are preliminary calibrated in marked in one longitudinal and one cross section by the means of height gauge and roundness measuring machine.

The angular rotation of the shaft is measured by a rotary encoder, attached in a device with contact roller, which touches the outer surface of the shaft, and a linear encoder measures the radial runout of the surface. This linear encoder is connected to the production machine’s carriage. The both encoders are connected by the means of a display gauge to a PC.

**Figure 1.** Principle diagram of shaft’s diameters measurement when based on the production machine

It is assumed that the carriage travel is straight and parallel to the shaft’s axis of rotation. The measuring devices of the machine determine the longitudinal and transverse displacement of the support.

2.2. **Measurement procedure**

The symbols and numeration are as follow:

- \( i \) – number of the current cross section;
- \( i = 1 \ldots n \)
- \( i = 1 \) – the cross section of the ring;
- \( i = n \) – the last measured cross section of the shaft;
- \( j \) – current measured point of cross section’s profile;
- \( j = 1 \ldots m, (m \text{ is even}) \)
- \( j = 1 \) – the marked points of both the shaft and ring.
- \( D_{li} \) – local diameter as a distance between two opposite points of the profile;
The measurement procedure is as it follows:

The tip of the linear encoder is brought in contact with the ring in the marked point \( j = 1 \) (Fig. 2) of the calibrated cross section \( i = 1 \) (Fig. 3). The readings \( A_{11} \) of the display gauge and also the reading \( B_{11} \) of device measuring the carriage transverse travel are input in the PC. Their sum is calculated:

\[
C_{11} = A_{11} + B_{11} \tag{1}
\]

The shaft is rotated by one revolution and by the values of the local runout, i.e. \( C_{j1} \), a diagram of the cross section is created (Fig. 3). The values \( \Delta_{11} \), \( \Delta_{1+\frac{m}{2},1} \) and \( e_{x11} \) are calculated using the diagram.

The value of \( D_{av1} \) is calculated by the equation:

\[
D_{av1} = 2(M_{11} - \Delta_{11} - e_{x11}), \tag{2}
\]

But

\[
D_{av1} = 2 \left( D_{11} - \Delta_{11} - \Delta_{1+\frac{m}{2},1} \right) \tag{3}
\]

The value of \( D_{11} \) is measured during the ring’s calibration. The following equation is drawn from substituting (3) into (2):

\[
M_{11} = 0,5 \left( D_{11} - \Delta_{11} - \Delta_{1+\frac{m}{2},1} \right) + \Delta_{11} + e_{x11} \tag{4}
\]
By moving the support the linear encoder is brought in contact with the shaft in the next \( i \)th section at a marked point \((j_i, \text{ where } j = 1)\) in the plane of the marked point of the ring.

The readings \( A_{1i} \) of the display gauge and \( B_{1i} \) of the device measuring the transverse displacement of the carriage are imputed in the PC and their sum \( C_{1i} \) is calculated:

\[
C_{1i} = A_{1i} + B_{1i}
\]  
(5)

The shaft is rotated at one turn and the results of the radial runout, i.e. by the values of \( C_{1i} \) the \( i \)th cross section’s roundness graph is drawn.

The values of \( \Delta_{1i} \) and \( e_{x1i} \) are evaluated by the roundness graph.

\[
R_{av_i} = M_{1i} - \Delta_{1i} - e_{x1i} \quad (6)
\]

\[
D_{av_i} = 2(M_{1i} - \Delta_{1i} - e_{x1i}) \quad (7)
\]

\[
M_{1i} = M_{11} + \Delta_{ci} \quad (8)
\]

\[
\Delta_{ci} = C_{1i} - C_{11} \quad (9)
\]

After substitution of (8) in (7):

\[
D_{av_i} = 2(M_{11} + \Delta_{ci} - \Delta_{1i} - e_{x1i}) \quad (10)
\]

The local diameter \( D_{av_i} \) can be evaluated as the distance between two opposite points:

\[
D_{ji} = D_{av_i} + \Delta_{ji} + \Delta_{j + \frac{m}{2}i} \quad (11)
\]

In the case of a straightness deviation of the movement of the carriage and a deviation from parallelism of this movement with respect to the axis of rotation, these deviations are determined by testing the geometrical accuracy of the production machine by appropriate methods.

Corresponding corrections of the values of \( C_{ji} \) shall be entered to exclude the influence of the both the deviations of straightness and parallelism of the carriage’s movement.

3. General sources of uncertainty

In accordance with this method, the model function (the functional relation between the diameter of the RMS circle \( D_{av_i} \) in a given section \( i \) and the input values) is given by the expression:

\[
D_{av_i} = D_{11} - \Delta_{i + \frac{k_i}{2}} + \Delta_{11} + 2e_{x11} + 2\Delta A_{1i} + 2\Delta B_{1i} - \Delta_{1i} - e_{x1i} \quad (11)
\]

It is assumed that the input quantities are non-correlated. Then:

\[
u(D_{av_i}) = \sqrt{u(D_{11})^2 + u(\Delta_{1 + \frac{k_i}{2}})^2 + u(\Delta_{11})^2 + 2u(e_{x11})^2 + 2u(\Delta A_{1i})^2 + u(\Delta B_{1i})^2 + u(\Delta_{1i})^2 + u(e_{x_{1i}})^2} \quad (12)
\]

but

\[
u(\Delta_{1 + \frac{k_i}{2}})^2 = u(\Delta_{11}) = u(\Delta A_{1i}) = u(\Delta_{1i}),
\]
then:

\[ u(D_{av_i}) = \sqrt{u(D_{11})^2 + 4(D_{11})^2 + 2u(e_{x_{11}})^2 + u(e_{x_{1i}})^2 + 2u(\Delta B_{1i})^2} \] (13)

\( u(D_{11}) \) is calculated by measuring instruments, which have been used during the calibration of the ring. When measuring with TESA MicroHite-M356, when the diameter of the ring is 200 mm, \( u(D_{11}) = 0.7 \mu m \).

\( u(\Delta_{11}) \) is defined by the accuracy of the measuring instrument. According to the datasheet of the linear encoder, the maximum error is ± 1 \( \mu m \).

With adopted rectangular distribution law (evaluation type B), \( u(\Delta_{11}) = \frac{2}{3.46} = 0.6 \mu m \).

\( u(e_{x_{11}}) \) and \( u(e_{x_{1i}}) \) depend on the roundness deviation values in the corresponding cross sections, and also on the errant runout of the axis of rotation. Research shows that when the number of profile’s measured points is more than 128, \( u(e_{x_{11}}) \) and \( u(e_{x_{1i}}) \) do not exceed 1\% of the roundness value [1].

\( u(\Delta B_{1i}) \) depends on the accuracy of the transverse movement of the carriage and requires special inspection.

For example, when assessing the accuracy of the positioning of a Hercules circular-grinder at the NKMZ - Kramatorsk, Ukraine, the estimated uncertainty \( u(\Delta B_{1i}) \) does not exceed 2.2 \( \mu m \).

4. Conclusion

1. To the important rotating surfaces of large-scaled shafts in the transport and heavy machinery industry, and other industrial sectors, do exist high requirements for the accuracy of the processing, respectively to the accuracy of their diameters.
2. The developed measurement method ensures high measurement accuracy when the shaft is based directly on production machine.
3. The method allows the determination of both the diameters of the RMS circles of the measured cross sections and of the local diameters as the distance between two opposite points of the profiles.
4. The review of major sources of uncertainty indicates that the method and measurement tools used for its implementation provide uncertainty of measurement less than the target-specific uncertainty associated with the tolerance.

5. References

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