Measurement of the macro geometry of large-scale rotary workpieces type "ring"

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Abstract. The measurement of geometric parameters (diameters and deviations of the shape and position) of large-sized details such as "ring" with the intended purpose is explored. The measurement system is built on the basis of a vertical turning machine, universal measuring instruments of linear displacement, specialized measuring instruments and the special software and allows to measure the respective parameters directly on the production machine. The developed measuring procedures are based on the determination of the deviation of the form and the position from the results of the radial and axial runout, with or without exclusion of the errant runout. In the first case, these results are brought to the virtual datum (axis) by introducing the appropriate corrections.

Key words: measurement, large-scale rotary workpieces, macro geometry.

1. Introduction
Large ring-shaped parts are one of the main functional elements of hydroelectric power plant turbines. The typical requirements for their macro geometry are shown in Fig. 1.

![Figure 1. Typical requirements for the macro geometry of large-scaled workpieces type "ring"](image)

For similar sized parts, measurement of these parameters is not a problem. However, for workpieces with sizes up to and over 10 m, very serious metrological problems arise due to the difficulty or inability to use routine (standard) measurement schemes.

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These problems can be solved with the developed measuring system, based on a vertical turning machine, universal linear displacement measuring instruments, specialized measuring equipment and software [3]. Measurements can be carried out directly at the workplace without removing the workpiece from the machine.

2. Principle of operation of the measuring system
The principle of operation of the measuring system is shown in fig.2 [3]. The vertical turning machine is a main component of it.

![Figure 2. Principle of operation, based on a vertical turning machine](image)

The measured part is located on the faceplate of the lathe and is centred relative to the axis of rotation by means of the jaws of the faceplate.

In the centre, roughly aligned with the axis of rotation, a mandrel is mounted with two reference rings 1 and 2, spaced apart at a distance H of each other. Both rings have calibrated diameters and roundness deviation EFK in marked cross sections, and ring 1 has also calibrated flatness deviation EFE of the front surface.

A linear sensor is installed in place of the tool post, and the rotation of the faceplate is measured by a rotary encoder built into a device, which contacts with the outer rotational surface of the workpiece.

Both the linear and rotary encoders are connected to the reading unit (the computing and reading unit of the system).

Both the horizontal (X axis) and vertical (Z axis) linear encoders are also connected to the reading unit. The primary measurement information is input for processing and registration to the computing unit (laptop) and the register unit (printer).
The software of the system ensures acquisition of primary measurement information, data processing and presentation of measurement results [1]. The results shall be documented in the form of relevant protocols presenting the information in textual and graphical form.

3. Methods of measurement

3.1. Measuring the deviation from roundness

Determination of the deviation from roundness is made on the results of the measurement of the radial runout in the respective cross sections both without and with excluding the errant runout by special programs [2].

In the first case, an exact datum (axis of rotation) is required, and in the second, this requirement is not necessary.

The decision to use one way or the other is made after evaluating the significance of the errant runout. When the errant runout is excluded, the results are brought to the virtual datum (axis of rotation) by entering appropriate corrections [2].

3.2. Measuring the deviation from flatness

The deviation from flatness is determined by the results of the measurement of the axial runout of one or more circular planar profiles by a given radius \( R \). When measuring one profile (one track), the program for calculating the deviation from roundness is used. On the profile diagram, fig. 3, \( \Delta_j \) represents the flatness deviation from the root mean square (RMS) associated plane at the \( j^{th} \) point of the profile \( (j = 1 \div k) \) and the eccentricity \( \Delta_x \) and \( \Delta_y \) determine the position and the magnitude of the projection \( e' (e_{xy}) \) of the normal vector to the RMS associated plane in a plane, perpendicular to the axis of rotation, i.e. in the \( XOY \) plane.

Figure 3. Profile diagram for calculating the deviation from roundness

When determining the deviation from flatness from the measurement results of the axial runout of more than one concentrically arranged round profiles, it is necessary, in addition to exact rotational...
movement of the workpiece (minimum axial runout) and straight, perpendicular to the axis of rotation, movement of the linear encoder, fig. 4.

Figure 4. Arrangement for the measurement of the flatness deviation, based on a vertical turning machine

The radius of the current circular profile is denoted by $R_i$ in fig. 4, where $i=1 \div n$. In fig. 4 $i=1 \div 4$.

Generally, the face is not perpendicular to the axis of rotation. The axial runout is measured along a radius $R_i$. There are determined the $z_{ij}$ coordinates of the points of the profile in the corresponding $XYZ$ coordinate system. It is assumed that the $Z$ axis coincides with the axis of rotation.

By the $z_{ij}$ values of all measured profiles, with the corresponding coordinates $x_{ij}$ and $y_{ij}$, an RMS associated plane is calculated and the deviations from flatness EFE are determined, as well as the position of the normal vector of this RMS plane relative to the axis of rotation.

3.3 Measurement of perpendicularity deviation

The deviation of perpendicularity of a given axial face relative to the axis of the rotary outer or inner surface is defined as the perpendicularity of its RMS associated plane to the axis of the rotational surface defined by the centers of the associated RMS circles of the profiles in at least two cross sections.

This is made in the following order:

1. Measure the axial runout of the given surface. After excluding the axial errant runout (if it is
significant), an RMS associated plane is built into the special program and the position of the normal vector is determined. It reflects the angle between the associated plane and the axis of rotation.

2. The radial runout shall be measured in at least two cross sections of the datum rotating surface. After excluding the errant radial runout (if significant), the position of the centers of their RMS associated circles relative to the axis of rotation is determined, i.e. the eccentricity $\Delta x$ and $\Delta y$, and the axis is defined by these two points. It is determined the angle between this axis and the axis of rotation. The difference between the two angles – this one of the normal vector and the axis of the rotational surface relative to the axis of rotation determines the perpendicularity deviation between the RMS plane of the face and the axis of the rotational surface.

When measuring in more than two cross sections of the rotary cylindrical surface, the axis is defined as the RMS straight line build by the centers of the RMS circles of the measured profiles.

### 3.4 Measurement of coaxiality deviation

Similarly, to 3.1, the radial runout is measured in at least two cross sections of the rotation surfaces under consideration. After corrections for radial errant runout (if significant), the eccentricities $\Delta x$ and $\Delta y$ of the centers of the RMS circles of the measured profiles with respect to the axis of rotation are determined, i.e. their position in the adopted coordinate system $XYZ$ (the $Z$ axis coincides with the axis of rotation). A corresponding axis is calculated by the coordinates of the centers of the RMS circles (such as the straight line connecting the centers of the two end sections, or as the RMS straight line, when the cross sections are more than two). The deviation from coaxiality is defined as the distance from the endpoints of the axis to the reference axis normal to it, or as a distance from the endpoints of the two axes to their common reference axis. All calculations are carried out by a special program, part of the measurement system software [1].

### 3.5 Measurement of the deviation from parallelism

The parallelism deviation of the two faces of rotational workpieces is determined by the angle between the normal vectors of the RMS planes of these faces obtained by measuring the axial runout (Figure 5).
Figure 5. Measuring the parallelism of the face surfaces of the ring-shaped rotary parts.
(a) a measurement scheme
(b) construction of normal vectors

The measurement is carried out in the following sequence.

1. Measure the axial runout of the two faces along a path of radius R.

After excluding the errant runout (if it is significant) by the results of the axial runout measurement, according to the special program, the RMS planes are built against the measured circular profiles, as well as the position of the normal vectors of these RMS planes relative to the axis of rotation.

2. The differences between the angles $\alpha$ and $\beta$ of the normal vectors of the two RMS planes relative to the axis of rotation determine the parallelism deviation in angular or linear quantities.

When measuring the axial runout in more than one circular profile of the face surfaces, RMS planes shall be constructed according to the procedure described in paragraph 3.2 and the position of the normal vectors of these planes relative to the axis of rotation shall be determined.

3.6. Measurement of the diameters of outer and inner rotating surfaces

3.6.1. Measurement of internal diameters

It is done in the following order:

− The radial runout of the internal rotational surfaces of the workpiece and the reference ring is measured in the respective cross sections.

− After corrections for the errant axial runout (if significant), profile diagrams of these two profiles are built. The roundness deviations shall be calculated by these graphs at the $j$th and the $(j + \frac{k}{2})$th points of the profiles, as well as the eccentricity of the centers of their RMS associated circles relative the axis of rotation, fig. 6.
It is measured the distance $L_1$ between the $j^{th}$ point of the profile of the workpiece and the $(j + \frac{k}{2})^{th}$ point of the reference ring, as well as the distance $L_2$ between the $(j + \frac{k}{2})^{th}$ point of the section profile of the workpiece and the $j^{th}$ point of the reference ring profile after rotating the face plate at $180^\circ$. When determining $L_1$ and $L_2$, both the linear encoders travel and the horizontal displacement of the carriage are taken into account.

On the basis of this primary measurement information, both the local diameters of the workpiece and the diameters of the RMS circles of the measured profile can be determined by the formulas:

$$D_j = L_1 + L_2 - r_{av} - \Delta_j' - r_{av} - \Delta_{j+k/2}''$$  \hspace{1cm} (1)

$$D_{av} = L_1 + L_2 - r_{av} - \Delta_j'' - r_{av} - \Delta_{j+k/2}' + \Delta_j' + \Delta_{j+k/2}'$$  \hspace{1cm} (2)

Where:

$\Delta_j'$ and $\Delta_{j+k/2}'$ are the deviations from roundness of the workpiece section at points $j$ and $j+k/2$;

$\Delta_j''$ and $\Delta_{j+k/2}''$ are the deviations from roundness of the reference ring at points $j$ and $j+k/2$.

The values of the average diameters of the reference ring are determined when it is calibrated.

3.6.2. Measurement of external diameters

The procedure is analogous to the measurement of internal diameters.

The radial runout of the outer rotational surfaces of the workpiece and the reference ring is measured in the respective sections.
After entering a correction for errant radial runout (if it is significant) profile graphs of the two circular profiles are built. The profile graphs reflect the deviation from roundness at \( j \)th and \((j + k/2)\)th points of the profiles, as well as the eccentricity of their RMS circles relative to the axis of rotation. The distances \( L_3 \), between the \( j \)th point of the profile of the of the workpiece and the \((j + k/2)\)th point of the reference ring, as well as the distance \( L_4 \) between the \((j + k/2)\)th points of the two profiles are determined after rotating the face plate at 180°.

\[
D_j = L_3 + L_4 + r_{av} + \Delta_j'' + r_{av} + \Delta_{j+k/2}''
\]

\[
D_{av} = L_3 + L_4 + r_{av} + \Delta_j'' + r_{av} + \Delta_{j+k/2}'' - \Delta_j' - \Delta_{j+k/2}'
\]

4. Conclusions

1. Measurement of geometric parameters of responsible large-scale ring-shaped parts is a serious metrological problem that can be solved successfully with the developed measurement system.

2. The system is based on a vertical turning machine, universal linear displacement measuring instruments, specialized measuring equipment and special software, that allow the measurement of the relevant parameters of the workpieces directly on the production machine.

The developed measurement methods are based on the determination of the deviation of the form and the position from the results of the radial and the axial runout measurement results with and without exclusion of the errant runout. In the first case, these results are matched to a virtual datum (axis) by entering appropriate corrections.

3. The methodology developed for measuring the diameters of the external and internal rotational surfaces of the workpieces allows the determination of both the local diameters and the diameters of the RMS circles of the measured profiles.

5. References

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