Research on Geometrical Errors of Geokhod Prototype Shell Based on Coordinate Control Data

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Abstract. The article contains results of a research on geometric accuracy of a geokhod prototype shell. The article outlines the general structural features of geokhod bodies, and the main principles of manufacturing in test production. An overview of approaches to modeling of shell error occurrence is given. The researches were conducted on the basis of data obtained by coordinate control over the stabilizing section shell. The data were studied by statistical methods and analyzed in terms of their compliance with previously proposed mathematical models of formation of geokhod shell inaccuracies. It is shown that available mathematical models can not completely explain the origin of all the errors. The authors attribute unexplained geokhod shell errors as deformations caused by welding.

1. Introduction

Currently, preparations are underway for commercializing of a new class of mining machines namely geokhods [1]. Geokhod is an apparatus intended for underground works of various purposes and locations in the rock space, and progressing in the rock mass using geo-environment. Design novelty of the machine requires new technologies for production of specific high-precision components and systems. A critical element of the geokhod is a shell (outer surface of the machine body), which interacts with the geological environment. Geometric precision of the shell affects the efficiency and service life of the machine as a whole, since it affects the resistance of rock mass to geohod progressing.

Three of the machine bodies are shelled: the head section, the adapter module outer body and the stabilizing section (figure. 1). The sections are structurally similar, have a cylindrical shape and are composed of shells, stiffening elements and flanges (figure. 2). Each shell is divided into four sectors. The sectors are lock-jointed and fastened with pins and bolts. The sections are large-sized and impact significantly on the production costs of the machine as a whole [2]. The nominal diameter of the shell is 3200 mm.

In order to assure assemblability, an assembly procedure, common in heavy engineering, is used, namely, pre-assembled locks are installed on the assembly plate in the specific mutual position. The locks form a frame to which the remaining structural elements are welded sequentially. This procedure reduces the amount of machining [3]; geometrical errors of the shell are mainly formed during assembly of the body. Inaccuracies of the shell are also affected by manufacturing errors. [4] describes how errors of mutual arrangement of sectors in the shell assembly and errors of sector shells affect the geometry errors of the shell shape. In [4] - [6], models for determining of ring shell errors are given, based on correction for geometric tolerances of mating surfaces. In [7] it is stated that the sequence of assembling of ring elements affects the assembling accuracy.

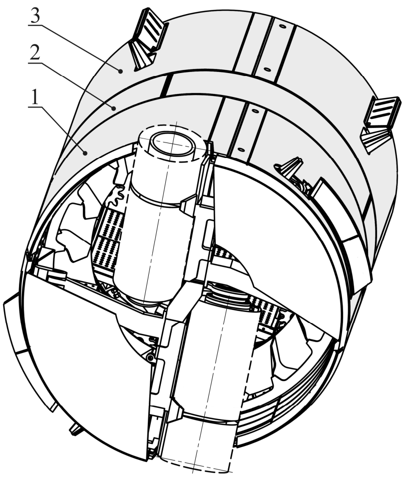

Figure 1. General view of geokhod prototype (shell is highlighted in gray): 1 - head section; 2 - adapter module outer body; 3 - stabilizing section.

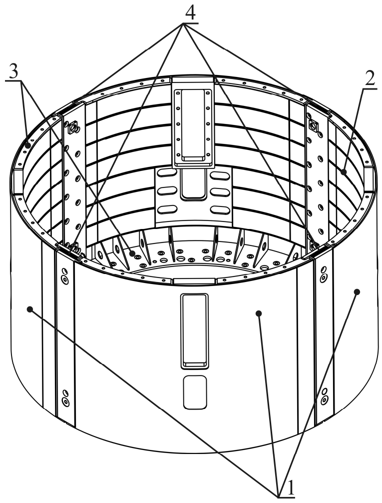

Figure 2. General view of stabilizing section: 1 - shell; 2 - stiffeners; 3 - flanges; 4 - locks.

The study is based on a geometrical approach only and do not include some error-factors, in particular, the deformation of shell parts caused by welding and pressure treatment. The objective is to study the actual shell accuracy of the geokhod prototype and identify factors, significantly affecting its accuracy.

2. Research Methods

For objective purposes the shell of the stabilizing section was studied. The body was subjected to coordinate control [8] using a mobile CMM “FARO Arm Edge 9”. For controlling the body frame was placed on the control plate by a particular flange. Next to the body a coordinate measuring machine (CMM) was installed. To expand the examination zone, control was performed from four directions. To obtain the coordinates of recorded points in a single coordinate system, affixment of CMM by calibrating cones was used for each position. Monitoring was carried out by determining of coordinates of point aggregates, evenly distributed over the shell surface.

To analyze and determine values of sector arrangement errors, measurement data was imported into a specially designed program. The program is based on development and analysis of regression models of cylindrical surfaces. Models of cylindrical surfaces were developed by approximation of point aggregates obtained by the measurements; they are expressed by the following system of equations:

$$
\begin{aligned}
&\sqrt{A^2+B^2+C^2}-r+\varepsilon_i=0\\
&A=-a_y z_i-\sqrt{1-a_x^2-a_y^2}\,(y_0-y_i)\\
&B=\sqrt{1-a_x^2-a_y^2}\,(x_0-x_i)+a_x z_i\\
&C=a_x(y_0-y_i)-a_y(x_0-x_i)\\
&a_z=\sqrt{1-a_x^2-a_y^2}
\end{aligned}
\qquad (1)
$$

x_i, y_i, z_i – coordinates of approximate points; a_x, a_y, a_z, x_0, y_0, r – unknown regression coefficients, having the following geometric meaning: a_x, a_y, a_z – coordinates of direction vector of approximating cylinder axis; x_0, y_0 – coordinates of the point of approximating cylinder axis path; r – radius of the approximating cylinder; ε_i – residues of the regression model.

The regression coefficients in equations (1) were determined by Gauss method [9], that is, from the condition

$$\sum_{i=1}^{n} \varepsilon_i^{\,2} \to \min \tag{2}$$

For determination of total geometrical deviations of the active surface points from the nominal shell geometry, a cylindrical surface model was developed based on approximation of the control dataset (figure. 3).

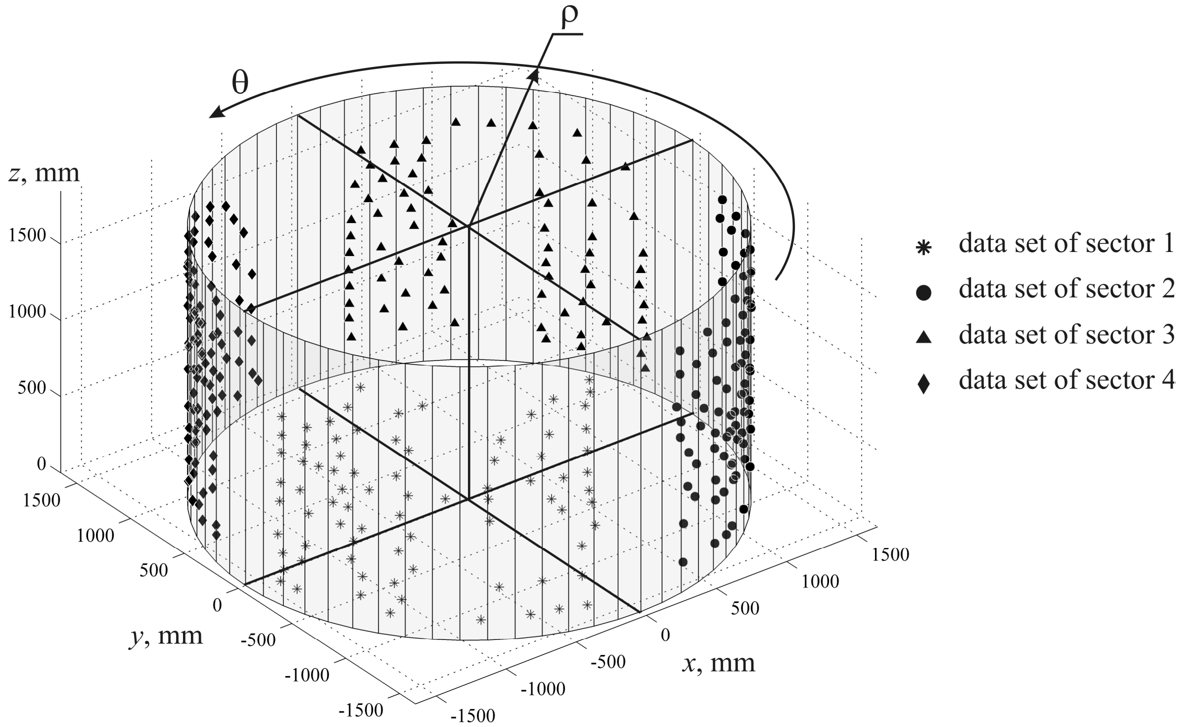

Figure 3. Data sets of measurements and a model of a cylindrical surface.

Model residuals were studied by correlation and regression analysis to identify systematic components in shell geometric errors in a sequence similar to that described in [10]. For this, point coordinates of each sector were transferred into a cylindrical coordinate system, associated with the sector axis $\theta z \rho$, and transformed into the first octant.

To determine values of deviations of separate sectors and deviations of sector radii, models of cylindrical surfaces were developed for each sector separately. Model residuals were also studied by correlation and regression analysis to identify systematic components in shell geometric errors [11].

3. Results and discussions

Table 1 shows model parameters of shell surfaces both completely and of separate sectors. Analysis shows that the body sectors are significantly different in their actual size and shape errors. However, errors are within the limits specified by the design documentation, but close to the critical values. The latter means that in mass production by this manufacturing method, there may be problems with assuring the accuracy of the geokhod shell assembly.

Table 1 Parameters of surface models

Parameter name	Shell in the whole	Sector 1	Sector 2	Sector 3	Sector 4
Radius of approximating cylinder, mm	1595.25	1595.01	1591.89	1604.45	1610.18
Standard deviation, mm	2.10	1.42	1.11	1.32	0.99
Maximum deviation, mm	5.25	2.76	2.85	3.23	1.83
Minimum deviation, mm	-4.50	-4.04	-3.10	-3.33	-2.82
Radius error, mm	9.75	6.80	5.95	6.56	4.65

We also note that errors in manufacturing and positioning of sectors are only a part of production errors. That is, in manufacturing process accuracy is conditioned by other factors; character and importance of these factors should be identified.Figure 4 shows the series of residuals of regression models of sector surfaces along angular coordinate θ. Specific changes of values in the set of residuals are noticeable for each sector. In each sector there are two "waves"; wave **bottoms** fall on sector edges and their middles. Similar regularities are observed in sectors 1, 2 and 4 particularly clearly. In sector 3 it is less pronounced.

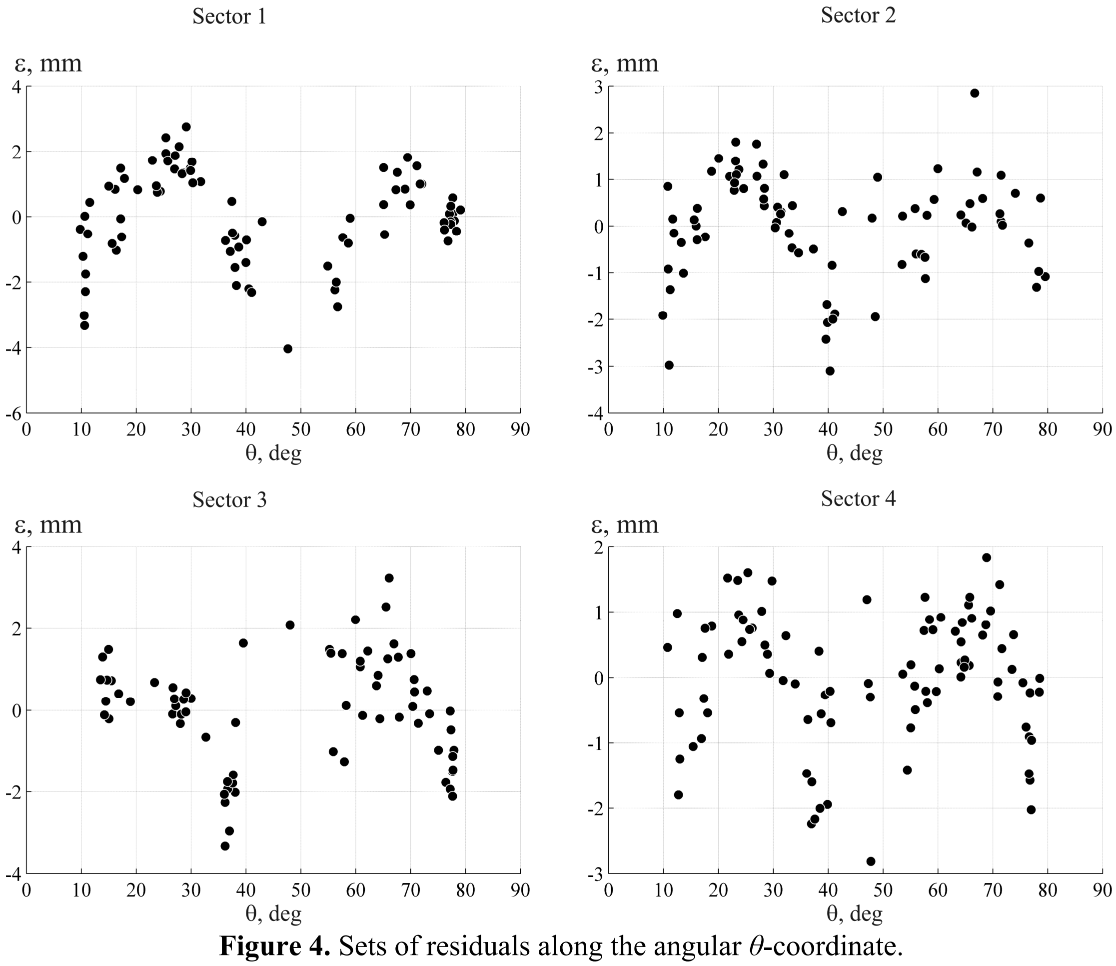

Figure 4. Sets of residuals along the angular θ-coordinate.

Figure 5 shows sets of residuals of sector surface regression models along z-coordinate. In the sets a dependence of residual values is less visible, however, reducing of residual magnitudes in the middle of each sector, can be observed. The results of the statistical analysis (see Table 2) indicate that mode of residuals is non-random. Critical values of statistics in this table are given for level of significance $\alpha = 0.05$.

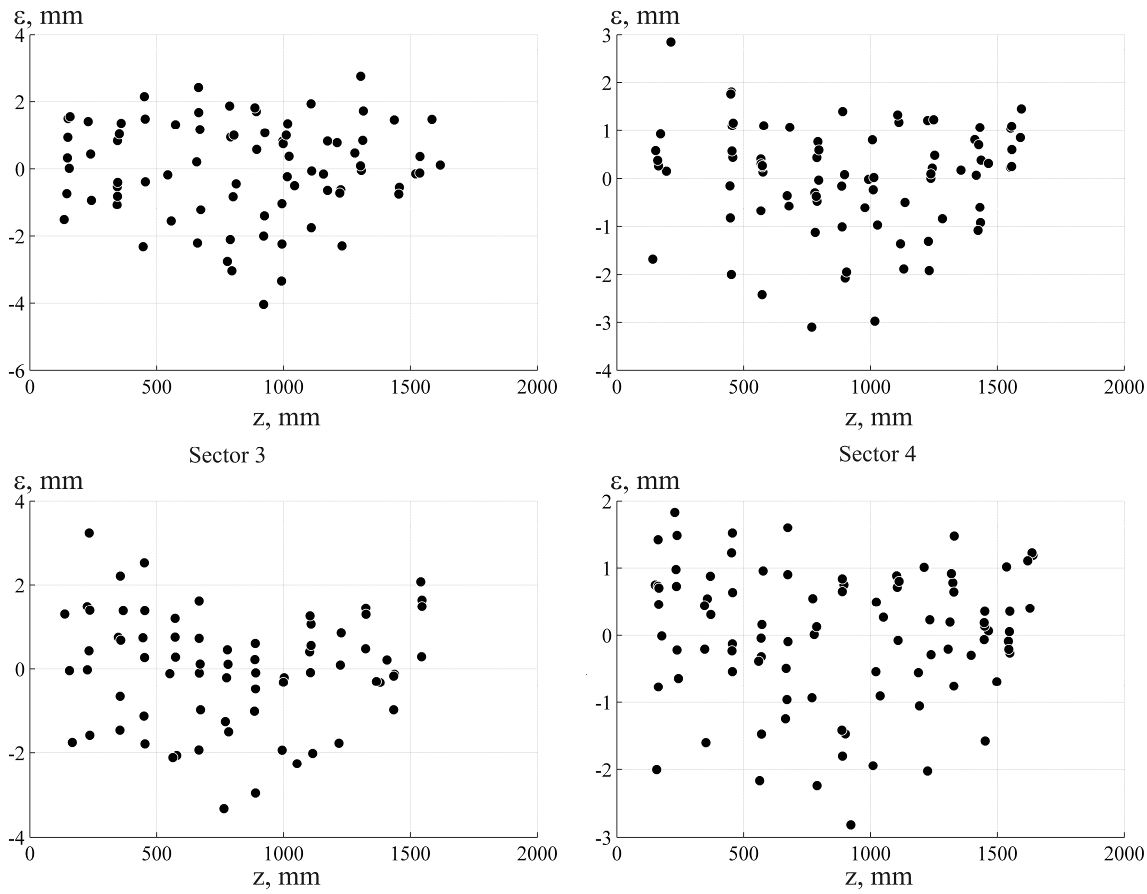

Figure 5. Sets of residuals along *z*-coordinate.

Statistic Epps-Pally criterion has shown that the residual sets in sector 1 and sector 2 do not correspond to the normal distribution law. Criterion of turning points has not determined the existence of a trend in residual sets $\varepsilon(\theta)$ and $\varepsilon(z)$ for any sector. Durbin-Watson statistic [12] has revealed that in residual sets $\varepsilon(\theta)$ autocorrelation is observed in each sector, in the same time there is no autocorrelation in residual sets $\varepsilon(z)$. Consequently, there are some regularities in shell point deviations from sector models; they depend on shell radius errors and assembling inaccuracy. In order to identify causes of regularity deviations, sets of control points were placed on sector scanning (figure. 6). In the scans structural elements (ribs, locks and massive elements) are traced. Magnitude of deviation points is designated with markers, corresponding to a specific range of deviations from the mean radius.

Image analysis (Figure 6) shows that negative-valued deviation points are concentrated around massive and rigid structural elements of sectors. Thus, "wave" bottoms in the middle of the sector (see Figure 4) are caused by a massive element namely a counter-rotation support member; and bottoms at the sector edges are caused by rigid elements namely locks. In this way, regularity in deviation changes is based on the regularity of the actual sector structure.

Table 2. Results of statistical analysis of model residuals.

Parameter name	Sector 1	Sector 2	Sector 3	Sector 4
Epps-Pally statistic	0.3363	0.6347	0.1949	0.7006
Epps-Pally statistic critical value	0.3754	0.3754	0.3751	0.3757
Number of turning points in $\varepsilon(\theta)$	51	51	44	57
Number of turning points in $\varepsilon(z)$	57	52	42	62
Critical number of turning points	44.7	44.7	39.1	51.5
Durbin-Watson statistic for $\varepsilon(\theta)$	0.7655	0.9767	0.7242	1.1818
Durbin-Watson statistic for $\varepsilon(z)$	1.9726	1.9843	2.0224	1.9245
	1.4650	1.4650	1.4330	1.4989
	1.5140	1.5140	1.4884	1.5433
	2.4860	2.4860	2.5116	2.4567
Durbin-Watson statistical significance bands	2.5350	2.5350	2.5670	2.5011

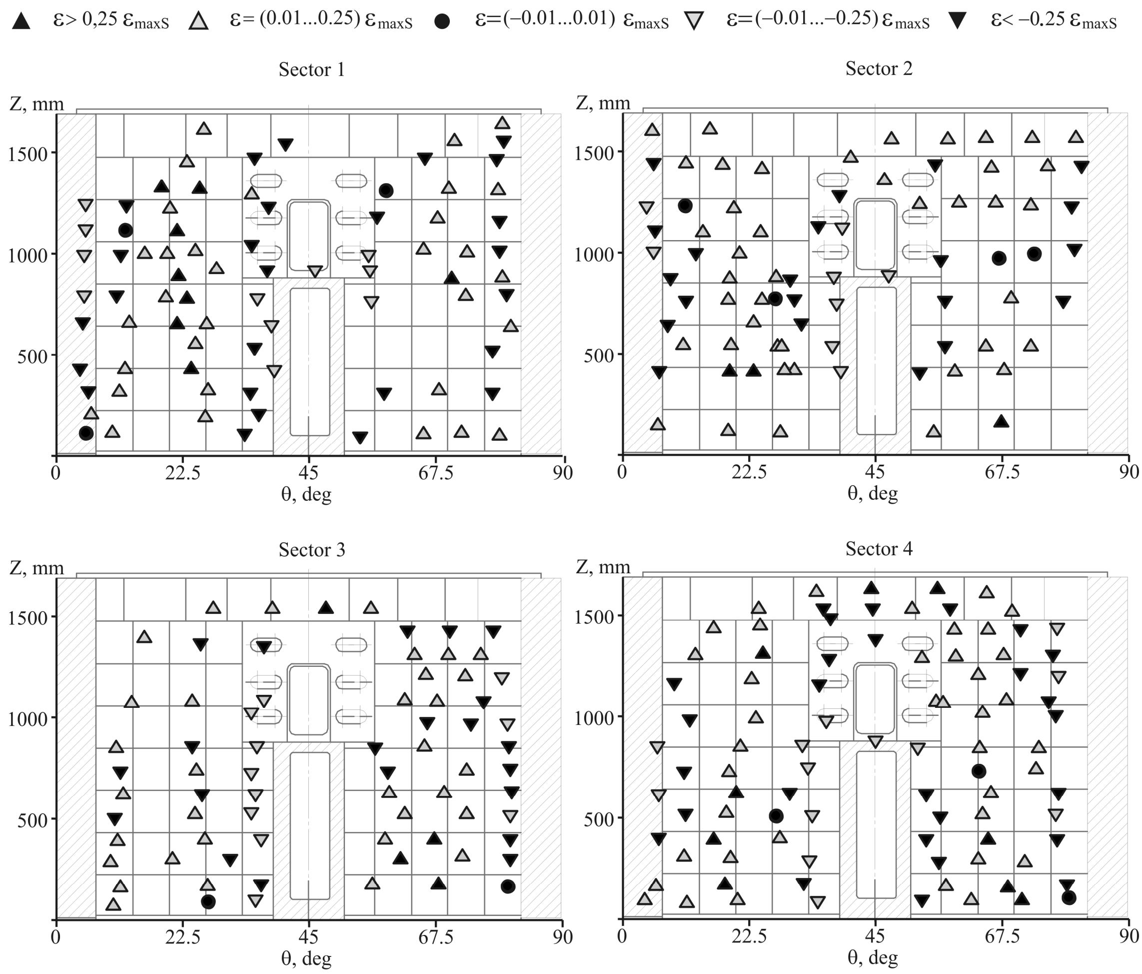

Figure 6 Deviation of measuring points from model mean radius on sector scans (ε_{maxS} – maximum difference between residual set terms for current sectors)

The only objective reason for such distribution of deviations in sectors may be deformations arising during welding [13]. Uneven rigidity leads to the fact that massive structural elements, without changing their geometry, change their position towards other elements and cause considerable deformations of less rigid elements. The results generally correlate with the results presented in [14], and require further development of shell error modeling by methods similar to those in [15], [16].

4. Conclusion

- Analysis of coordinate measuring of the stabilizing section shell shows that deviations from the geometric precision, close to critical values, are foreseeable at manufacturing of geokhod bodies.
- The causes of deviations are shell manufacturing errors, assembling inaccuracy of sector positioning and other causes, that have not been determined until now.
- It has been established that mode of shell surface deviations is caused by sector structure which is composed of elements of different rigidity. This gives reason to believe that shell deviations that are not caused by shell manufacturing errors and assembling inaccuracies, are deformations caused by welding.

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