Integrated approach to the technology of manufacturing electrostatic gyro rotors

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Abstract. Technological solutions based on the integrated approach are presented, which optimize the manufacturing process and satisfy the requirements imposed on spherical rotors of electrostatic gyros. System modeling is used to study the main stages of defining the rotor functional parameters and to construct a system of models that determines the coordinated processes of diffusion welding, precision sphere lapping and rotor weight correction. The practical results of rotor manufacturing and the prospects for accuracy enhancing are provided.

Introduction. To improve a gyro with electrostatically suspended rotor (ESG), a group of problems should be solved, the most important being meeting more stringent requirements for the spherical rotor parameters [1,2]. In the electrostatic suspension the forces normal to the surface act on the rotor, so the rotor shaped as an ideal sphere will have zero moment of electrostatic forces relative to the center [3]. Therefore, to minimize error torques, strict requirements are imposed not only on the imbalance, but also on the parameters determining the rotor shape. Thus, axial and radial imbalances should not exceed hundredths of a micrometer, and amplitudes of harmonics of shape deviations from the given configuration should not exceed hundredths and thousandths of a micrometer. The quality of the rotor spherical surface corresponds to the 13th roughness class, which meets the requirements for metal optics. Satisfying such stringent requirements is an extremely difficult technical task, therefore, special attention is given to the technological aspects of ESG spherical rotor manufacturing.

This problem can be solved only using an integrated approach to the design of the technological process of rotor manufacturing, when the features and interrelations are taken into account, and main technological operations of rotor manufacturing are coordinated. The integrated approach is most effective when using system modeling at all stages of the rotor manufacturing, when its functional parameters are successively defined [4].

Problem statement. The technology for manufacturing spherical gyro rotors is determined by the need to solve a number of technological problems to provide the required functional parameters of the rotor, which include: geometric (diameter, shape, non-circularity), dynamic (moment of inertia and imbalance), optical (contrast and uniformity of contrast of optical pattern on the rotor surface),
tribological (surface wear resistance). The provision of these parameters within the required tolerances is determined by the choice of technological methods and aids of rotor manufacturing.

The purpose of the study is to identify and coordinate a set of interrelated technical solutions enhancing the technological capabilities of the manufacturing process and increasing the precision of the ESG rotor.

1. System modeling of the rotor manufacturing process

System modeling is associated with the study of the cyclic algorithm [4] shown in Fig. 1, which includes three main stages of the existing technology defining the rotor functional parameters.

![Fig. 1. Algorithm of rotor manufacturing process.](image)

At the first stage, a spherical blank is shaped and the moments of inertia of the rotor are created. The main operation in the manufacture of a hollow rotor is vacuum diffusion welding (VDW) of the joint planes of two hemispherical shells with a changing wall thickness monotonically reduced from equator to the pole. At the second stage, the most important parameters are provided, which largely determine the accuracy of the rotor: imbalances and shape. At the final third stage, optical and tribotechnical properties are defined, and final weight correction is performed if required [4].

Describing the algorithm in detail, the rotor manufacturing process can be represented as a structural chain of sequential states $S_1, S_2, S_3, \ldots$, see (1).

$$\ldots \rightarrow S_i(F_1, F_2, \ldots F_i)\{TT\}_i \rightarrow \rightarrow S_i:1\rightarrow F_1, F_2, \ldots F_{i:1}\{TT\}_i:1, \rightarrow S_i:2(F_1, F_2, \ldots F_{i:2})\{TT\}_i:2, \rightarrow \ldots$$

Each of these states corresponds to a set of parameters $F_1, F_2, F_3, \ldots$ defined at this stage of the process, and transition from one state to another is determined by the transition operators $P_1, P_2, P_3, \ldots$, each being associated with a specific technological operation. Obviously, in the state $S_i$ the parameters $F_i$ should correspond to the set of technical requirements $\{TT\}_i$. Transition from one state to another,
for example $S_i \rightarrow S_{i+1}$ is associated on the one hand with the need to keep the parameter set $(F_1, F_2 \ldots F_i)$ within the limits determined by the set of technical requirements $\{TT\}_i$, and on the other hand with the definition of the new functional parameter $F_{i+1}$. At the next transition $S_{i+1} \rightarrow S_{i+2}$, this parameter $F_{i+1}$ is already included in the number of saved parameters and the parameter $S_{i+2}$ is defined.

The rotor manufacturing technology is based on two fundamental principles. First, each previous operation should create the most optimal conditions and prerequisites for performing subsequent operations, and second, at each subsequent operation it is necessary to save the values of the rotor parameters obtained in the previous operation. At the same time, the effectiveness of the technological design process is conditioned by:

1) development of a system of coordinated models that determine the main stages of rotor shaping;

2) optimization of definition of rotor functional parameters by shifting the operations of creating these parameters to the finishing stages of manufacture to reduce the number of parameters saved during processing;

3) minimizing the relationships between the parameters defined within one transition $P_i$ between adjacent rotor states, for example, between the shape accuracy, diameter and imbalance in the cyclic block 2 of the algorithm (Fig. 1).

The formulated provisions are implemented by developing the models of diffusion welding, sphere lapping and rotor balancing processes with the identification of the most optimal sequence for the definition of rotor functional parameters.

2. Shaping the spherical blank

The main operation at this stage is DVW of the joint planes of beryllium hemispheres to ensure their reliable connection and create the rotor moments of inertia. The welding process was optimized to increase the efficiency of subsequent rotor balancing and lapping. Using the known technical solutions [5, 6] the welding process scheme was developed and the control factors and conditions of the welding process were determined.

In the considered DVW scheme, the axial thermal interference pressure is applied to the flanges of the hemispheres, which is determined by different values of the linear thermal expansion factors (LTEF) of the welding module components (Fig. 2): flanges of beryllium hemispheres 1, punches 2 and ties 3. DVW modeling is based on the use of expressions determining the successive states of the welding module system: initial - with the clearance between the parts $\Delta_0$, intermediate - when the initial clearance $\Delta_0$ between the flanges of the hemispheres being welded becomes equal to zero (at the joining temperature $T_j$), and the final one - under the welding temperature $T_w$ [7]. The most effective technical solution [8] uses the localization of welding pressure by making an annular collar
with inner diameter \( D_1 \) and outer diameter \( D_3 \) on the surface of each punch in contact with the flanges of the hemispheres. This welding scheme provides a uniform structure of welding stresses, which increases the accuracy of rotor lapping. During further isothermal holding, stress is relaxed and the rotor is thermally stabilized with relaxation of stresses due to flange deformation, which creates conditions for increasing the accuracy of rotor shaping during subsequent processing.

Modeling the thermomechanical welding cycle and stress distribution in the deformed area of hemispheres by the finite element analysis method was used to identify technical solutions for DVW optimization based on control of successive deformation of the welding module components and upsetting deformation during uniaxial compression of the hemisphere flanges with compensation of this deformation. In this case, the deformation process occurs in the conditions of high-temperature creep of beryllium, and the stage of relaxation of welding stresses is provided in the thermomechanical welding cycle, which minimizes stresses in the rotor and provides conditions for improving the rotor manufacturing accuracy [7, 8]. The optimized variables in the target functions that determine the DVW are the control factors and significant process parameters: joining \( T_j \) and welding \( T_w \) temperatures, geometric parameters and properties of the materials of the welding module components, and specific properties of beryllium used to make ESG rotors [9].

3. Precision sphere lapping

Weight correction used to eliminate the rotor imbalance and shaping of precision sphere with a preset diameter are the most important operations that determine the gyro accuracy, and the required imbalance and shaping accuracy are normalized to hundredths and thousandths of a micrometer. The second stage of the technological process is the longest and most laborious. At this stage, it is necessary to solve two main problems: to create specialized non-standard equipment [10, 11] providing these accuracies, and to eliminate contradictions between the operations of directed lapping during imbalance correction and spherelapping [4].

To ensure the required kinematics and operating conditions, a three-spindle lapping machine was traditionally used, with a drive, whose rotary motion was transferred to the laps using reduction gear.

![Fig. 3. Lapping machine with uniformly spaced spindles](image)

Initially, the equipment was improved by transferring rotation to each spindle from its step motor controlled according to a preset autonomous program. Machines with a planar three-spindle layout have limitations on the sphere processing accuracy, so later a fundamentally new equipment was developed with four uniformly spaced spindles (Fig. 3) [12].

The model of rotor motion with cup laps was constructed and used to provide uniform processing. During the modeling we studied the tribological processes inlap-rotor pairs with various materials of
laps and abrasive suspensions. The developed model of the processed sphere motion is used to determine the optimal spatial location of the laps and the parameters of their motion [13]. Step-by-step modernization and improvement of the equipment design enabled reduction of the amplitudes of harmonics (starting with the third) to a few nanometers for beryllium rotors.

**Fig. 4. Rotor balancing diagram.**

Elimination of contradictions between the operations of directed lapping for weight correction and spherallapping is associated with the construction of asymptotic iterative process that ensures alternating minimizations of the imbalance and of rotor shape deviation from the desired one. This problem can be solved by promising methods such as imbalance correction by forming recesses with desired configuration on the rotor surface [14], which will be discussed in more detail below.

Figure 4 shows a diagram of the balancing process. Compared to the iterative process, in which balancing can be performed along lines 1 and 2, the method of local laser evaporation of a point mass can abruptly change the rotor imbalance. The second stage of weight correction is needed if the diameter has reached the specified values and directed lapping cannot be applied for further balancing.

Lines 3 and 4 are used in the balancing process within integrated approach, when, along with the first traditional stage of weight correction by directed lapping, the second correction stage is used without changing the rotor shape and diameter, for example by laser evaporation of a local point mass of material from the rotor surface. In this case, the segments $A_0 3^*$ and $A_0 4^*$ define the first, and segments $3^* 1^*$ and $4^* 1^*$ define the second stage of rotor balancing.

The structural chain of successive rotor states in the balancing process, where the states are determined by optimized parameters such as imbalances, rotor diameter and shape, can be represented as constructing rotor manufacturing routes, which, in addition to the weight correction by directed lapping include alternative weight correction operations.

Providing the required imbalance and rotor shape is largely related to metrological aspects. It has been established that the rotor controlled geometric parameters are comparable with the errors of the Talyrond 73 roundness measurement instrument used [15].

It was shown that the major error was due to the spindle error (Fig. 5), which can be considered constant over a sufficiently long time interval. Therefore a method to account for this measurement error was proposed and implemented.

The second problem is conditioned by the fact that requirements for the shape of the rotor surface were imposed on the amplitudes of shape harmonics obtained by averaging measurements in four meridional sections. Usually the research is limited to the fourth - sixth harmonics of the Fourier series since the amplitudes of the harmonics rapidly decrease for the higher-frequency terms of the series. The disadvantage of this averaging method is that the phase of the harmonics in each specific section is not taken into account, and this parameter manifests itself as a random variable causing errors in the
rotor shape estimation. Yu.G. Martynenko [3] found that the most complete information on the rotor shape is given by the parameters describing the so-called virtual volume, which allow more adequate modeling of the forces and moments acting on a body in electrostatic suspension. The virtual volume is understood as the rotor virtual shape described by the average rotor radius for the given latitude [16]. Such representation of the shape additionally using the Legendre expansion increases the ESG accuracy by creating a more adequate mathematical model of its behavior by taking into account the physics of rotor interaction with the suspension force field when describing the rotor shape. At the same time, in manufacture and certification of rotor parameters, one of the main criteria is the degree of deviation of the surface shape from the basic one, being a sphere for a solid rotor, and an ellipsoid for a hollow rotor depending on ESG type.

Fig. 5. Spindle error of the Talyrond 73.

4. Final weight correction and definition of tribotechnical and optical parameters
Tribotechnical and optical parameters are defined in the process of applying a thin-film coating of titanium nitride to the rotor surface and creating a raster pattern on the coating by laser marking [4]. The main task in this case is to preserve the imbalance and shape obtained in the previous balancing and spherelapping operations, which is associated with the solution of multi-criteria and multi-purpose problems. As mentioned above, after the second stage and fulfilling the requirements for the rotor shape and diameter, the required imbalance is not always provided. This problem can be solved during the coating by choosing the most optimal option from alternative technical solutions [17], for example, correcting the imbalance by displacing the center of the spherical sprayed layer relative to the rotor geometric center [4, 18]. Promising methods such as imbalance correction by forming recesses of desired configuration on the rotor surface can also be employed [14].

Application of coating and marking can also change the imbalance obtained at the second stage. It may also require an additional final weight correction, which should lead to minimal distortion of the rotor shape in the areas adjacent to the power electrodes. Then the above-mentioned method of imbalance correction by forming recesses of the desired configuration on the rotor surface is very effective. In this case, the target functions provide optimization of inclination angle $\theta$ of the recess axis to the rotor dynamic axis and the weight of material removed from the recess.

To increase the efficiency of this weight correction process, a model was developed based on laser evaporation of local point mass at the final stage of rotor manufacturing [19, 20], which determines two stages of the process:

- partial elimination of the initial imbalance $c_{i1}$ by directed lapping with a tube lap at the first stage by reducing the vector radial component with minimal distortion of the rotor shape;
- final balancing by forming a recess of desired weight on the rotor surface outside the zone with the raster pattern (Fig. 6), when the imbalance axial component is mostly eliminated and the rotor shape described by the virtual volume method is barely changed. According to the
formulated proposals, this enhances the efficiency by shifting the imbalance correction to the final stage of rotor manufacturing and by reducing the relationship between shape accuracy, diameter and imbalance within one transition $P_i$ between rotor successive states.

![Diagram of rotor final weight correction](image)

**Fig. 6.** Rotor final weight correction. 1 - rotor, 2 - recess formed during the evaporation of local mass, 3 - spherical segment in which the recess is made, $\theta$ - inclination angle of the recess axis to the dynamic axis $O_1O_2$.

A promising line of research is the creation of methods to control the optical characteristics of raster pattern by modifying the surface when applying nanoscale layers of pigment-forming materials [21]. This reduces the thickness of the coating and the intensity of laser action on the rotor, decreasing the influence of these factors on the shape accuracy and rotor imbalance.

The integrated use of the presented technical solutions provided the possibility of manufacturing rotors with static imbalance of max hundredths of a micrometer and amplitudes of harmonics of shape deviations from the given configuration of hundredths and thousandths of a micrometer. The dimensional stability of the rotors has been improved, determined by analyzing the changes in the second $A_2$ and third $A_3$ harmonics of the amplitude spectrum of deviations from the spherical shape, which are most characteristic for estimating the rotor shape and operating conditions.

**Conclusions**

Based on an integrated approach, a system of models has been developed that determines the main stages of the manufacturing process and the scientifically grounded set of coordinated technical solutions to define the functional parameters of ESG rotors. It has been proved that the choice of the sequence and control of the process of defining the rotor functional parameters with the identification of alternative methods and technological aids form an important technological aspect. At the same time, the optimization of the technology results from taking the features of the previous operations into account and creating the conditions for the most efficient performance of subsequent operations when defining the rotor functional parameters, and conditions are provided to define these parameters at the final manufacturing stages and to reduce the number of saved parameters during processing. The greatest efficiency can be provided by identifying technical solutions able to solve multipurpose and multicriteria problems.
Experimental verification has confirmed the validity of the theoretical provisions and the adequacy of the developed models and showed the possibility of obtaining ESG rotors with shape accuracy and imbalance of hundredths and thousandths of a micrometer.

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