Technological aspects of thin film formation on the rotor of spherical gyroscopes

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Abstract. A scheme of fixation in a technological device during thin film deposition process is considered for the spherical rotor of electrostatic and cryogenic gyroscopes. Calculations of the fixing scheme parameters, based on the contrast image zone location are presented. The influence of the fixing scheme on the rotor imbalance is evaluated. The dependence of the difference between the initial and post-deposition imbalance on rotor and thin film parameters is obtained. Comparison of the dependencies obtained for electrostatic and cryogenic gyroscope rotor is shown.

Introduction

Accuracy parameters of spherical gyroscopes, either electrostatic or cryogenic ones, substantially depend on production process of sensitive elements and especially rotors. The requirements for shape and imbalance deviations of rotors amount to tenths and hundredths of micrometer. The technology of rotor production consists of mechanical processing followed by forming thin films of titanium nitride or niobium for electrostatic or cryogenic gyroscopes, respectively. The last stage of technology is laser marking of the film surface to form contrast images for the read-out system functioning [1–3]. Obviously, the scheme of rotor fixing and positioning during the thin film deposition has influence on rotor parameters. Considering the fact that the contrast images are located along the equatorial line and limited by latitude angle, the fixing points should be placed in a zone free from images. The purpose of this research is to study the fixing scheme and its influence on the spherical rotor imbalance after the deposition process.

1. Calculation of rotor fixing scheme parameters

The thin film for spherical rotors is formed by cathodic arc deposition using a special technological device [4]. Since a fixing scheme in two diametrical supports is insecure [5], in the proposed scheme the rotor is fixed with four spring-loaded needle supports (Fig.1).

The fixing points a, b, c and d correspond to the tops of a regular pyramid. As it was mentioned before, the fixing points should be located in a zone free from images and limited by the angle a and the circle 4. The distance between the fixing points is defined by the length of the chord ab which is equal to bc and ac. In an ideal case, when the axes of couplings 10 and 11 and the rotor axis O*O* coincide, the fixing points a, b and c are located on the circle 4. Accordingly, it is possible to calculate the maximal distance between the fixing points:
where $R$ is the radius of the rotor. Taking into account the couplings position error defined by the angle $\beta$, the radius $r = O_a a$ of the circle circumscribed around the triangle formed by the fixing points $a$, $b$, and $c$ is:

$$ r = \frac{\sqrt{3}}{3} l_{\alpha_{\max}}^\beta, $$

where $l_{\alpha_{\max}}^\beta$ is the maximal distance between the fixing points, taking into account the position error angle $\beta$. On the other hand,

$$ O_a a = (R \cos \alpha - R \sin \alpha \cdot \tan \beta) \cos \beta. $$

By substituting the expression (3) into (2), we obtain the following formula of the maximal distance between the fixing points:

$$ l_{\alpha_{\max}}^\beta = \sqrt{3}(R \cos \alpha - R \sin \alpha \cdot \tan \beta) \cos \beta $$

Assuming that angle $\beta$ is small, the formula (4) will be as follows:

$$ l_{\alpha_{\max}}^\beta \approx \sqrt{3}R \cos \alpha - \sqrt{3}R \cos \alpha \sin \alpha \approx l_{\alpha_{\max}}^\beta - \sqrt{3}R \sin \alpha. $$

The expressions (4) and (5) show the dependence of the technological device parameter (the maximal distance between the fixing points) on the rotor characteristic (latitude angle of image location). For example, for the rotor radius of 5 mm, the image location latitude angle of 57° (which correspond to electrostatic and cryogenic gyroscope rotors), and the couplings position error of 5°, the maximal distance between the fixing points is 4.1 mm. Thus, using the presented calculations, it is possible to exclude the location of the fixing points from the image zone by varying the distance between the needle supports.

2. Influence of fixing scheme on rotor imbalance

Considering the fixing scheme, the position of the supports is asymmetrical relative to the rotor. The coupling with three needle supports has a shielding effect during the deposition process in the area of its location. This area can be represented as a spherical segment described by the angle $\theta_{\max}$, where the coating thickness deviates from the nominal value (Fig. 2).

The radius of the rotor with thin film can be presented by following relationship:

$$ R(\theta) = \begin{cases} R_p + h - \Delta h \cos^2 (\theta - \theta_{\max}) \theta < \theta_{\max} \\ R_p + h, \theta > \theta_{\max}. \end{cases} $$

Fig.1. Rotor fixing scheme. 1 – rotor; 2 – contrast image zone limited by angle $\alpha$; 3 – spherical segment free from contrast images; 4 – limiting circles of contrast image zone; $\beta$ – angle of couplings position error; 5 – zone of fixing points location (taking into account the error $\beta$); 6, 7, 8, 9 – needle supports; 10, 11 – couplings.

Fig.2. Rotor with coating thickness deviation caused by shielding effect. 1 – rotor with a radius $R_p$ before deposition; 2 – thin film.
where $R_p$ is the radius of the rotor after mechanical processing; $h$ is the film thickness (in the zone free from shielding effect); $\Delta h$ is thickness deviation.

The shielding effect leads to mass center displacement. The expression describing the post-deposition imbalance caused by the mass center $z$ displacement is as follows:

$$
\varepsilon_k = \frac{1}{M_0} \int_{V_z} z \rho dV = \frac{1}{M_0} \left( \int_{V_{sphere}} z \rho_{rot} dV - \int_{V_{film}} z \rho_{film} dV \right)
$$

where $V_z$ is the volume of the rotor with thin film; $M_0$ is the mass of the rotor; $\rho_{rot}$ is the density of the rotor material; and $\rho_{film}$ is the density of the thin film material.

The first integral from (6) is solved as $M_0 \varepsilon_0$, where $\varepsilon_0$ is the initial imbalance of the rotor after mechanical processing. Neglecting the elements with $\Delta h$ being to the power higher than the first, the expression (6) has the form:

$$
\varepsilon_k \approx \varepsilon_0 - \frac{1}{M_0} \rho_{film} 2\pi (R_p + h) \Delta h \frac{\pi^2 - \pi^2 \cos(\theta_{max}) - 2\theta_{max}^2}{8(\pi^2 - \theta_{max}^2)}
$$

(7)

Upon introducing the function $Q$ depending on the angle $\theta_{max}$:

$$
Q(\theta_{max}) = \frac{\pi^2 - \pi^2 \cos(\theta_{max}) - 2\theta_{max}^2}{2(\pi^2 - \theta_{max}^2)}
$$

the expression (7) is:

$$
\varepsilon_k \approx \varepsilon_0 - \frac{1}{M_0} \rho_{film} \frac{\pi}{2} (R_p + h) \Delta h \cdot Q'(\theta_{max}),
$$

(8)

where $M_0$ is the mass of the rotor, defined as $\rho_{rot} V_z$.

In the expression (8), the angle function $Q(\theta_{max})$ and the densities of the rotor and film materials have a significant influence on the difference between the initial and post-deposition imbalance. In case of rotors in electrostatic and cryogenic gyroscopes, where the densities of the beryllium and carbon substrates are approximately equal (1.85 g/cm$^3$ [6] and 1.8-2.1 g/cm$^3$ [7], respectively), the densities of the film material have higher influence. For the electrostatic gyroscope rotor, the film material is titanium nitride with the density of 5.44 g/cm$^3$, and for the cryogenic gyroscope rotor, it is niobium with the density of 8.5 g/cm$^3$ [8]. The requirement for final imbalance for electrostatic and cryogenic gyroscope rotors is not more than 0.02 $\mu$m [9] and 0.05 $\mu$m [10], respectively. The dependence of the difference between the initial and post-deposition imbalance on the thickness deviation for different angles $\theta_{max}$ for electrostatic and cryogenic gyroscope rotors is presented in the Fig.3.

Fig.3. Dependence of the difference between the initial and post-deposition imbalance on the thickness deviation and different angles $\theta_{max}$. 

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As can be seen in the Fig. 3, the value of imbalance difference increases with the growth of the angle $\theta_{\text{max}}$ defining the shielding effect. Thus, the reduction of the distance $l_\beta$ between the fixing points will provide lower shielding effect and, therefore, less change of imbalance during the deposition. Also, higher density of niobium material leads to increased imbalance, so the shielding effect has a more significant impact on cryogenic gyroscope rotor parameters.

However, this effect can be used as a method of imbalance correction after the mechanical processing in a range where thickness deviation $\Delta h$ does not cause the shape deviation above the required value. In this case, the rotor imbalance vector is orientated towards the coupling with three needle supports.

Conclusions
The fixing scheme of spherical rotors during the deposition process has been considered. The calculation of position of fixing points located in the zone free from contrast images has been presented. The dependence of the technological device parameters on the rotor characteristics has been obtained. The suggested calculations and scheme make it possible to minimize the rotor position alignment error and thus, to eliminate local defects during laser marking process.

The shielding effect of the fixing scheme on the spherical rotor imbalance has been studied. The dependence of the rotor post-deposition imbalance variation on the density of the rotor and film material and on the angle defined by the fixing elements position has been shown. The obtained results increase the technological possibilities due to the use of the revealed dependence in decreasing the imbalance variation and correcting the imbalance after previous mechanical processing operation.

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