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Physico-mathematical modeling methods for the pressure distribution determination in the gas-dynamic bearing gap of the ball gyroscope

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Abstract. The considering problem in the article connects with solution methods of the specific questions in gas-dynamic lubrication theory. The comparative analysis of analytical and numerical methods for the calculating gas-dynamic bearing characteristics is provided. The main applying aspects of them for the solving of specific gas lubrication theory points are presented. This research is carried out for the investigated gap bearing geometry for the designed ball gyroscope construction. The main mathematical equation and results of developed numerical simulation for the pressure distribution determination are shown.

1 Introduction

During the gyroscopic technology development, rotor bearing construction has remained one of the main gyroscopy problems. Gas lubrication application for the gyroscopic devices was determined by the tendency of increasing the gyroscope accuracy, rigidity and operating life. Using gas lubrication allowed decreasing frictional losses, enhance the durability and reliability. Gas bearings can work under the severe mechanical influences, increased radiation conditions, and in the wide range of temperatures and ambient pressure without losing its performance characteristics [1].

Ball gyroscopes have the specific field of application. Generally, they are used as sensitive elements for precision inertial navigation systems and gyro-stabilized platforms. The ball gyroscope construction is different from others in quite high resistance to overloads and impacts of external dynamic effects. The main type of gas bearings as a part of such gyroscopic devices are gas-dynamic bearings (GDB). This is due to a strong requirement for gyroscope weight and size parameters; gas-dynamic bearings do not require additional excess pressure sources such as gas bearings with an external pressurization.

The final selection of the rotor bearing type and parameters depends on the field of application, design features, and developing purposes. These aspects of research work were considered in the previous article [2]. It should be emphasized that hemispherical configuration of the GDB working surfaces has been selected as of providing the sufficient reserves for the load capacity and stiffness, as well as the spin axis position stability and the low level of natural vibration frequency.

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It is expected that basing on such type of gyroscope with the hemispherical configuration of GDB will allow creating a reliable and sufficiently accurate inertial navigation system for the solution of relevant problems of metrological drilling process maintaining.

2 Materials and methods

Gas lubrication theory is a part of viscous fluid dynamics where the fact that the gas layer thickness is much less than its other dimensions. The gas lubrication flow is generally laminar, and inertial forces are negligible in comparison with viscous friction forces. Therefore, lubrication theory basic equation (Reynolds equation) is a consequence of the equilibrium equations between forces of viscous friction and normal pressure [3]. Basically, the Reynolds equation solution is a key component of the solving mathematical modeling problems.

Reynolds differential equation for the gas lubrication is [4, 5]:

$$\frac{\partial}{\partial x}\left(h^3 \frac{p}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3 \frac{p}{\mu}\frac{\partial p}{\partial z}\right)=12pV_y+6\frac{\partial}{\partial x}\left(pV_x h\right)+6\frac{\partial}{\partial z}\left(pV_z h\right)+12h\frac{dp}{dt}, \quad (1)$$

where V_x, V_y, V_z - relative velocity components of the working surfaces in the tangential, radial and axial direction, respectively; h - lubricating layer thickness in the considering section; μ - dynamic viscosity; p - pressure. Taking into account the injection ability of grooves (if available) and geometric features of the bearing profile, Reynolds equation becomes in a more complicated form.

The main calculating methods of the gas bearing characteristics are analytical and numerical methods; among the lasts - application software packages. The most important principle components of any mathematical modeling methods are [4]:

1. Preparation of the phenomenon, process or task mathematical model;
2. The transition from the continuous mathematical model to the discrete model;
3. Writing the algorithm for the discrete model (sequence of computational steps, and transferring to a computer system);
4. Software package configuration for the certain task;
5. Getting results and their analysis.

Certainly, the analytical methods are the most preferable methods of mathematical modeling. They provide the deeper dive into the physical nature occurring in the lubricating layer phenomenon and, therefore, help to avoid mistakes in the statement of task. Additionally, using the special application oriented software packages for solving the system of equations which was obtained by analytical method, it is possible to carry out the high-precision calculation of "rotor-bearing" system for evaluating effectiveness, reliability and efficiency of the designed unit.

On the other hand, numerical methods over the past few years have also gained the quite powerful tools for the certain gas dynamics problems solving. They can solve the problems of three-dimensional steady and unsteady flows, laminar and turbulent flows with free surfaces, multiphase flow problems, with and without cavitations, chemical reactions, and etc. Application software packages are used for simplifying and advancing the mathematical modeling. But it should be realized that it occurs with some restrictions.

Despite of various advantages and disadvantages of a particular method, the theoretical and numerical simulation of the gas bearing characteristics exceptionally large and significant. Whereas, the experiment in this area is extremely difficult and expensive as of ultrathin gap (several microns) between the working surfaces.

The following part, numerical experiment for the pressure distribution determination in the gas-dynamic bearing gap of the developed ball gyroscope using ANSYS software will be presented.

3 Numerical simulation

The main gas-dynamic bearing characteristics are: pressure distribution in the gap bearing, bearing capacity accordingly, bearing rigidity, and the value of viscous friction momentum. Geometry of interest for the ball rotor with gas-dynamic suspension is represented in Figure 1 schematically.

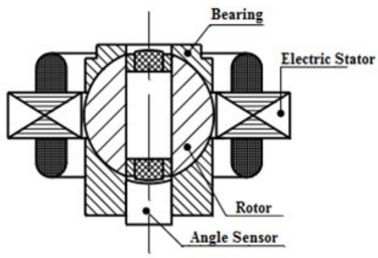

Fig. 1. Considering gap geometry of the "rotor-bearing" system.

The rotor is a ball with diameter 28,587 mm. It is made from steel SHKH15. During the rotation it is supported by two hemispherical gas-dynamic bearings. The hemispherical bowls surface is smooth and modified so that the spherical diameter for 10 microns more than the actual rotor diameter (5 mm per side). This difference provides an initial clearance which is obligatory for the working at the gas lubrication operational mode. The ball rotor is driven by the magnetic field of the three-phase asynchronous electric stator. Maximum voltage for the stator is 40 V and frequency is 1000 Hz. The rotor has three rotational degrees of freedom. In case, when the rotor and stator magnetic field rotating axes are coincided, the electromagnetic torque is applied to the rotor. The nominal rotor speed is 16 000 rev/min; the maximum angular momentum of the ball gyroscope is 0,013 N·m. The total layout length is 68 mm and the diameter - 77 mm; weight - not more than 1 kg. Dimensions are not the final [6].

The results of the gas-dynamic bearing calculation modeling for determination of the pressure distribution in the gap are provided in the following. The calculations were performed using application software package module in ANSYS - FLUENT. The mathematical formulation of this problem, in this case, has the general terms, as package flexibility requires from developers to cover the widest range of tasks. Besides of the aforementioned geometrical parameters, it is necessary to specify that the air was selected as the gaseous medium; type of gaseous medium model - incompressible ideal gas; conditions for pressure and temperature - normal. The mathematical model is based on solving the system of equations of fundamental laws of mass, momentum, and energy conservation. The system closes the initial and boundary conditions, as well as defining relations [6].

The pressure distribution across the gap on the ball rotor and hemispherical bowls surfaces are presented in Figure 2 *a)* and *b)*.

According to numerical simulation, the total pressure has the value up to 2067,3 Pa. The pressure distribution models on the bearings provided as spheres as rotor geometry. It is formed by two hemispherical bowls. This form is quite appropriate since the problem is axially symmetric. The models show that the maximal pressure is located in the equator areas as the radius here is maximal. Also, the width of the equatorial maximal pressure band on the rotor is greater than the hemispherical bowls. This is due to the fact that the rotor is movable part relative to the fixed bearing system. So, in the character of pressure distribution, dynamic component of the pressure plays an important role from the rotor rotation. Since the more the rotation speed of the moving part, the more contribution dynamic component, and it makes the total operating pressure higher.

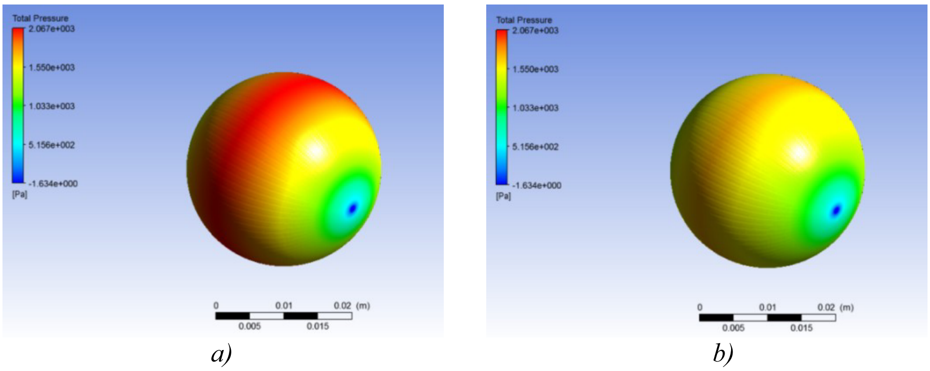

Fig. 2. *a)* 3D model of the pressure distribution on the ball rotor surface at the nominal rotation speed 16 000 rev/min; *b)* 3D model of the pressure distribution on the hemispherical bowl surface at the same nominal rotation speed.

Using the given results about the pressure distribution field, it is possible to calculate other characteristics as following: load bearing capacity, rigidity, and provide estimation of viscous friction momentum. These calculations are carried out by analytical way and presented in the [6].

4 Conclusions

Currently, the numerical methods which are used for solving the gas lubrication problems cannot be as a full and enough replacement of analytical methods. Modern software packages are very objective. The complete solution of the gas lubrication mixed problem including calculation of the gas flow in the lubrication layer, temperature field determination, solution of dynamics and optimization problems cannot be carried out in any of the existing special software packages. For the solution of certain and application tasks, for instance, determination of the pressure field in the bearing gap, as was considered in the article, numerical methods can be like an accompanying tool. By their means, the preliminary assessment of the gas bearing parameters can be achieved. Also, some basic processes can be visualized, as well as using the program results for further calculations.

Recognizing the versatility and powerful of numerical methods, the analytical methods should not be underestimated. Based on their advantages, it is possible to analyze some specific and limit cases which allow checking the solution correctness obtained by numerical methods.

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