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The Author of Precision Gyroscope

V. G. Peshekhonov[a, b, *]
[a]*Concern CSRI Elektropribor, JSC, St. Petersburg, 197046 Russia*
[b]*ITMO University, St. Petersburg, 197101 Russia*
**e-mail: office@eprib.ru*

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Abstract—The paper presents the brief history of development of a precision gyroscope with electrostatic suspension of rotor; the main problems of constructing a gyro with a hollow rotor, as well as their solutions found by the chief designer A.S. Anfinogenov are discussed.

Keywords: electrostatic gyroscope, inertial navigation, hollow rotor

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INTRODUCTION

It has been ninety years since the birth of Anatolii Anfinogenov (1930–2003), the designer of precision gyroscope with electrostatic suspension of spherical rotor (ESG). It is the only gyroscope which has not had an alternative for forty years; it is unique in terms of accuracy and engineering solutions.

The purpose of this article is to tell about the problems of the ESG development and how they were solved by its chief designer Anfinogenov and his team. More details about Anfinogenov's life and work can be found in the book [1], which includes the articles written by Anfinogenov and his co-workers, as well as some memoirs about him.

Anfinogenov's biography is seemingly uneventful. He was born and lived all his life in Leningrad–Saint Petersburg. He stayed in the city from the first till the last days of the Leningrad siege. In 1948, he entered the Leningrad Electrotechnical Institute (LETI), where he studied very well and at the same time achieved excellent athletic feats: he was a player of the famous basketball team of LETI which won the Leningrad championship; within the city's picked team, he also took part in the national championship.

In 1954, he graduated from LETI with qualification in electrophysical engineering, and was sent to work for the Special Design Bureau of the State Union Plant, but after a few months he was transferred to the research institute NII-303 (later named CSRI Elektropribor) and started working at the laboratory of gyroscopic equipment. Since then, he never changed his area of activities.

Even the first works of the young engineer were evidently innovative. He developed a line of amplifiers based on semiconductor elements, which substituted the tube amplifiers. His next project was the development of gyroscopic servosystems, including gearless ones, which found wide application. In the middle of 1960-s, Anfinogenov started the main work of his life: the ESG development.

HISTORY OF ESG

The idea of ESG was proposed by A. Nordsieck (USA) in 1954. The potential advantage of ESG against other types of mechanical gyroscopes was obvious: due to the contactless suspension of the rotor in the electric field, there was no friction in the rotor

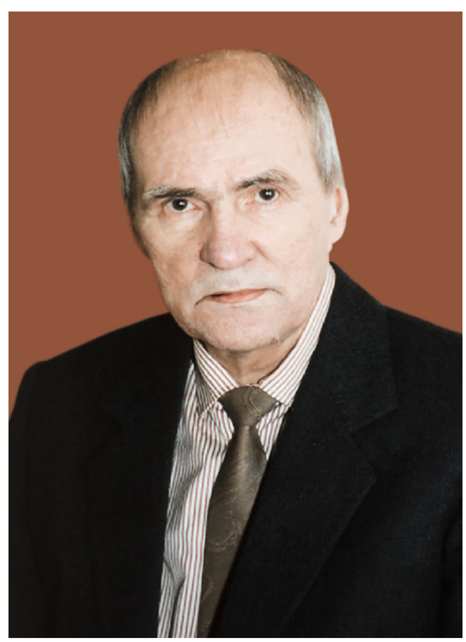

Fig. 1. A.S. Anfinogenov.

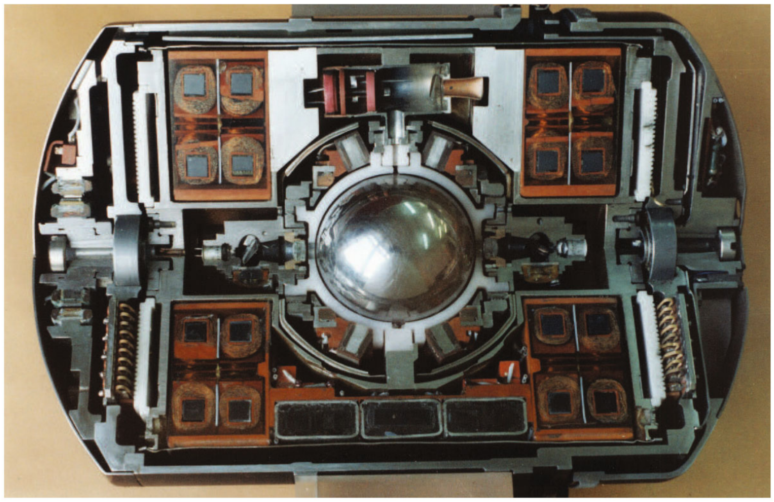

Fig. 2. ESG in section.

Fig. 3. A.S. Anfinogenov reports to the USSR Navy Commander-in-Chief about the ESG test results at the test bench of CSRI Elektropribor.

support, which is one of the main factors limiting the accuracy of rotary gyroscopes.

This advantage was demanded a decade later, when the gyroscope engineers in a number of countries started the R&D work on a precision inertial navigation system (INS). At the CSRI Elektropribor, Anfinogenov and several employees started researching the problem of a precision ESG development. He had only the most general information about the work in this field in the US [2]. It is a common knowledge that technological solutions in gyroscopy are not shared, and Anfinogenov went all the way on his own.

It was necessary to study the theory of electromagnetic field with regard to the mechanics of a rapidly rotating solid body. For the first time in the history of gyroscopy, a vacuum high-voltage device was designed and a package of engineering and metrological solutions was developed to ensure the production of a gyroscope with the accuracy characteristics that had been deemed unachievable before. On this basis, a new production complex was to be created.

In 1966 the ESG project was supported by the Military Industrial Committee of the USSR Council of Ministers who issued a resolution to involve 28 dedicated organizations in this task. At the first stage

(1966–1968), the pilot research was performed, some results of which are reflected in publications [3–7]. The experiments were carried out on a laboratory set assembled from available instruments and materials. This bulky structure looked like anything but a gyroscope; nevertheless, it helped to test a number of ideas.

The gyroscope development began within the R&D project (1969–1973) and lasted for almost twenty years. This period can be conventionally divided into two stages. The first stage (1969–1979) was dedicated to the development of the ESG design and technological and metrological capabilities. In the end of this stage, industrial production of gyroscopes started. To ensure the ESG production, more than ten new divisions were formed and equipped, such as departments, laboratories, and production sites.

At the second stage, the work on the ESG accuracy and reliability improvement was performed. This was carried out in parallel with the delivery of gyroscopes, and each new result was implemented in the next delivery batch. Finally, a precision ESG and a precision INS based on it were created.

The truly titanic work of A.S. Anfinogenov and his team was crowned with one of the greatest successes of Russian gyroscopy.

It should be noted for information that a lot of large companies in our country and abroad tried to develop the ESG, but only two of them coped with the task: CSRI Elektropribor in Russia and Honeywell in the US.

ESG: PROBLEMS AND SOLUTIONS

The ESG operating principle is based on the well-known relation of electrodynamics

$$\vec{f} = \frac{E^2}{8\pi}\vec{n},$$

where $\vec{f}$ is the vector of density of the ponderomotive forces of electric field on the surface of a perfect conductor; E is the electric field intensity at the conductor surface; $\vec{n}$ is the unit vector of normal to this surface. If a uniform conductor has the shape of an ideal sphere and is surrounded by a spherical stator, the torque of the forces acting on the rotor is zero. In the case of a gyroscope, this means that its drift rate will be zero.

However, without taking special measures an electrostatic suspension is unstable: in accordance with Earnshaw's theorem [8], a conducting body cannot rest in stable equilibrium in the electrostatic field. Therefore, a servosystem is required to measure the rotor displacement and to restore its position by controlling the suspension field.[1] Thanks to Anfinogenov's experience in developing the gyroscopic servosystems, this problem was solved.

The ponderomotive force determined by the above formula is small, and the field intensity should be significant at the rotor surface to ensure an acceptable supportive force of the suspension. For this reason, the ESG is a high-voltage device with a small distance between the stator and the rotor.

Since the distance between the rotor and the stator is small, the equation for isotropic linear suspension has a solution when the number of suspension electrodes is equal to 6, 8, 12, and 20. This determines the structure of the suspension, which has the maximum stiffness. If the above conditions are met, the problem of constructing an ESG is reduced to creating a rotor which would be as close as possible to the ideal, i.e. a concentrically homogeneous rotor.

The rotor material should have high electric conductivity, magnetic permeability close to one, low density (due to the limited supportive force of the suspension), and the minimum ratio of density to Young modulus (to minimize the rotor deformation during rotation). Beryllium meets these requirements best of all. To ensure the uniformity of the rotor, beryllium blanks are made from powder by isostatic pressing. This technology was developed specifically for the ESG.

From the possible designs of the rotor (solid or hollow rotor), A.S. Anfinogenov chose a more promising one from the point of view of achieving high accuracy, but at the same time much more complex in terms of implementation: a hollow rotor assembled from two hemispheres. It was necessary to create a thin-walled electrically homogeneous structure which would retain a spherical shape with an error of no more than 0.1 microns and have an imbalance of less than 0.05 microns when rotating at an angular rate of about tens of thousands rpm.

To orient the rotor, an ellipsoid of inertia should be formed by thickening the walls from the pole towards the equator. To compensate for the rotor deformation during rotation, caused by centrifugal forces, it is necessary make it in the shape of ellipsoid stretched towards the poles.

Welding of the rotor hemispheres should not lead to its heterogeneity. Electric charges concentrate on any heterogeneity, which leads to lower time constant of the gyroscope with respect to the misalignment angle. Attempts to borrow the experience from organizations which develop welding technologies were not a success. Moreover, the country's leader in this field, Paton Institute for Electric Welding, concluded that the required non-detachable connection was impossible to implement.

Extensive research carried out by technology researchers of CSRI Elektropribor provided a solution to the problem: using the diffusion welding with unique custom equipment, vacuum-tight fixed joint

[1] Properly speaking, in this case the suspension will not be electrostatic any more, but the rotor displacement rate is negligibly small compared to the velocity of electromagnetic waves, so the static approximation is justified.

was obtained, which does not deteriorate the electrical homogeneity of the rotor.

Generally, the rotor was created due to the development of a large number of original technological processes and special equipment. Their scientific level is evidenced by the fact that the employees of CSRI Elektropribor defended one doctoral and more than ten candidate theses dedicated to the engineering problems of ESG development.

Creating a stator also required some non-trivial solutions. The system of electrodes should be placed on a dielectric vacuum-tight supporting structure which provides strong adhesion of the electrodes and has an internal surface differing from the spherical one by no more than 1 μm. The production of especially pure corundum ceramics was organized; most of the technological processes to form the stator were borrowed from electro-vacuum production, but with one fundamental difference: the supporting structure processing and the electrodes spattering were performed on a spherical surface instead of a flat one.

An important feature of the ESG development process, which largely pre-determined the entire positive result, was the consistency of structural design stages and the development of technological tools. At the same time, the technology for manufacturing the ESG units and elements was characterized by a large number of unobvious, intuitively paradoxical engineering solutions and numerous unusual techniques, methods and tools which were tried thanks to A.S. Anfinogenov's initiative.

A number of units embedded in the ESG were developed by specialized organizations. For instance, the autocollimation sensor which determines the attitude of the rotor with an error less than 1 arcsec was designed at the Leningrad Optical and Mechanical Association (LOMO); and the getter-ion pump which maintains vacuum at no worse than 10^{-7} Torr during the ESG operation was developed by Vekshinskii Institute of Vacuum Engineering.

The work on the ESG operational reliability improvement was carried out in steps. Since a gyroscope is a high-voltage device, it is vulnerable to a breakdown between the stator and the rotor. This problem was solved due to vacuuming, thorough cleaning of parts, and strong adhesion of the electrodes to the ceramic hemispheres, which eliminates the separation of electrode particles under the action of the suspension field.

The next step was to ensure high reliability of the suspension electronics, which required, among other things, miniaturization, reconfiguration and relocation of the electronic blocks from the instrument cabinet directly into the gyroscope casing. To avoid the gyroscope destruction during an emergency power cut, the problem of trouble-free of the rotor/stator touching was solved. Based on the study of triboscopic properties of various materials, a pair with a low coefficient of friction was selected: titanium nitride coating of the rotor and diamond-like coating of touching beds on the stator. Appropriate coating technologies were developed to preserve the spherical shape and balance of the rotor, which solved the problem of trouble-free rotor/stator touching.

To analyze the influence of the ESG structural elements on the accuracy characteristics, a mathematical model has been constructed, according to which the rates of the gyroscope drift along the axes perpendicular to the kinetic moment vector are determined by harmonic series; the argument of their trigonometric functions is the angle between the gravity vector and the vector of the gyroscope's kinetic moment. This model is valid when the gyroscope is installed in a follow up gimbal suspension which ensures the alignment of one of the ESG casing axes with the rotation axis of the rotor, and the casing rotation about this axis. In the first approximation, the series are reduced to trinomials whose coefficients have a clear physical meaning. The first coefficients of a series, which do not depend on gravity, are determined by the rotor connection with the casing (i.e., the time constant of the gyroscope). As the technology of seamless welding of the rotor hemispheres were improving, these coefficients were decreasing. For modern ESG, one of these coefficients is negligible, as well as the coefficients determined by the electric losses in the rotor and by the tangent forces affecting the rotor. The remaining coefficients are proportional to the gravity acceleration and are determined, on the one hand, by the rotor balancing, and on the other hand, by the non-sphericity of the rotor surface at the operating frequency of rotation with a non-rigid suspension of the rotor.

The construction of a model where the coefficients are uniquely related to the physical factors, in this case, to the rotor parameters, is a typical example of Anfinogenov's approach to solving any new complicated problem. The described model has been used for more than forty years.

The development of the ESG production technologies did not always run in a timely fashion, and the Chief Designer A. S. Anfinogenov had to defend his brainchild many times. He was sure that all problems would be finally solved, and such a confidence along with the credibility of arguments always found support at last.

CONCLUSIONS

A.S. Anfinogenov and his team came close to fulfilling the dream of gyroscopy engineers since the time of L. Foucault: to create a free (uncontrolled) gyroscope. It has been forty years that the ESG has remained the most accurate gyroscope, and today, when most of mechanical gyroscopes have almost been replaced with wave-optical ones, the ESG is still the second to none.

Nevertheless, A.S. Anfinogenov is little known among the gyrocsopy specialists. This is probably due to local applications of the ESG and the veil of top secrecy which hid the process of this gyroscope development. Anatolii Anfinogenov was not upset with this situation, he was a non-public person and did not yearn for broad recognition.

Anfinogenov was certainly aware of his worth; he knew that the scientists and specialists who worked with him unconditionally believed and supported him; that his colleagues at CSRI Elektropribor respected him, and that was enough for him. It took a lot of efforts to persuade Anatolii Anfinogenov to submit his works to the approval of the scientific community. He brilliantly defended his candidate's dissertation in 1990, and his doctorate thesis in 1993.

A.S. Afinogenov was also calm about awards. He was awarded the Order of the Red Banner of Labor in 1971 and won the State Prize in 1984. He was the only awardee of the Prize named after N.N. Ostryakov, the first chief designer of gyroscopic devices in our country, who got this prize twice: in 1979 and in 1996. It seems that most of all he valued the title of an Honored Inventor of the Russian Federation, awarded to him by a decree of the President of the Russian Federation in 2001. His 142 inventor's certificates and 4 patents most fully reflected his creative achievements in course of the ESG development.

CSRI Elektropribor treasures the memory of Anatolii Anfinogenov. A book dedicated to his work has already been mentioned [1]; from 2005 to 2010, there was A.S. Anfinogenov Foundation for Support of Students and Postgraduates, and in 2011, the Anfinogenov Prize was established, which is awarded for the best paper on gyroscopy issues, presented at the annual major conference of young scientists "Navigation and Motion Control". On the event of the 90th anniversary of the birth of Anatolii Anfinogenov, a dedicated exhibition was opened in one of the halls of the Institute's museum. We, the few colleagues of Anfinogenov who are still working at Elektropribor, and the new generation of Elektropribor staff, do our best to preserve the memory of this prominent scientist and his outstanding achievements.

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* The works 3–7 were also re-published in [1].