STATE RESEARCH CENTER OF THE RUSSIAN FEDERATION
CONCERN CSRI ELEKTROPRIBOR, JSC

25th ANNIVERSARY
SAINT PETERSBURG
INTERNATIONAL CONFERENCE
ON INTEGRATED
NAVIGATION SYSTEMS

PROCEEDINGS

28 – 30 May 2018
Saint Petersburg, Russia

CO-SPONSORED BY:

- RUSSIAN FOUNDATION FOR BASIC RESEARCH
- INTERNATIONAL PUBLIC ASSOCIATION – ACADEMY OF NAVIGATION AND MOTION CONTROL (ANMC)
- NATIONAL RESEARCH UNIVERSITY ITMO, RUSSIA
- AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS (AIAA)
- INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS – AEROSPACE AND ELECTRONIC SYSTEMS SOCIETY (IEEE AESS)
- INSTITUT FRANÇAIS DE NAVIGATION (IFN)
- DEUTSCHE GESELLSCHAFT FUER ORTUNG UND NAVIGATION (DGON) GERMAN INSTITUTE OF NAVIGATION
- JOURNAL GYROSCOPY AND NAVIGATION

In the present publication the plenary and poster papers of the 25th Anniversary Saint Petersburg International Conference on Integrated Navigation Systems (28 – 30 May, 2018) are presented.

*The poster papers marked with *.*

Editor-in-Chief

Academician of RAS
Vladimir G. Peshekhonov

CONTENTS

SESSION I – INTEGRATED SYSTEMS

SESSION II - INERTIAL SYSTEMS AND SENSORS

SESSION III – SPACECRAFT CONTROL AND NAVIGATION

FUSED QUARTZ CYLINDRICAL RESONATORS FOR LOW-COST VIBRATION GYROSCOPES*

Boris Lunin
MSU n.a. Lomonosov
Moscow, Russia
luninboris@yandex.ru

Mikhail Basarab
Bauman MSTU
Moscow, Russia
bmic@mail.ru

Aleksei Yurin
Bauman MSTU
Moscow, Russia
yualex@rambler.ru

Evgenii Chumankin
JSC "ANPP "TEMP-AVIA"
Arzamas, Russia
che54@mail.ru

***Abstract* – A design and a simple technology for manufacturing an inexpensive fused quartz resonator for general-purpose CVG are proposed. The resonator was made from a piece of commercially available fused quartz tube. The proposed technology makes it possible to manufacture such a resonator without the use of precision machining, while the Q-factor of such a resonator in the kilohertz frequency range reaches 1 000 000. Although this Q- factor is much lower than that of precision quartz resonators, it considerably exceeds the Q-factor of cylindrical metal resonators. In addition, the stability of the dissipative characteristics of the resonator is greatly increased, which, on the whole, reduces the systematic drift of the device and its instability. These advantages make it possible to significantly improve the accuracy of a general-purpose CVG without increasing its cost price. The design and characteristics of such resonators, the methods of their balancing, as well as the possible constructive appearance of CVG on their basis are given.**

Keywords—Coriolis vibratory gyroscope; fused quartz

I. INTRODUCTION

In recent years, Coriolis vibratory gyroscopes (CVG), whose functioning is based on the precession of elastic standing waves in a thin-walled mechanical resonator under the action of Coriolis forces, have become quite widespread. The motion of the wave pattern relative to the resonator is proportional to its angular displacement, therefore, by analyzing the motion of the wave pattern relative to the resonator, the angular displacement of the CVG is calculated. As for other types of gyroscopes, the errors of CVG are determined by defects of various kinds. In particular, CVG possesses a significant systematic drift of the standing wave due to the inhomogeneity of internal friction in the mechanical resonator. According to [1, 2], the amplitude of the rate of this drift is

$$\dot{\theta} = \frac{\pi f}{4}\left(\frac{1}{Q_1} - \frac{1}{Q_2}\right),$$

where θ is orientation of the wave pattern in the resonator; f is the natural frequency of oscillations; Q_1, Q_2 are the Q-factors of the resonator with respect to its viscosity axes.

The systematic drift of the CVG is taken into account by calibrating the instrument. However, the stability of this drift (and hence the accuracy of its compensation) depends on the stability of the characteristics of the resonator. Suppose that in an ideal resonator ($Q_1=Q_2=Q$), the internal friction along one of the viscosity axes slightly changed and became equal to $(Q+\Delta Q)^{-1}$. Then there will be an additional systematic drift with the angular rate amplitude

$$\dot{\theta} = \frac{\pi f}{4} \frac{\xi}{Q},$$

where $\xi = \Delta Q / (Q + \Delta Q)$ is the internal friction relative instability.

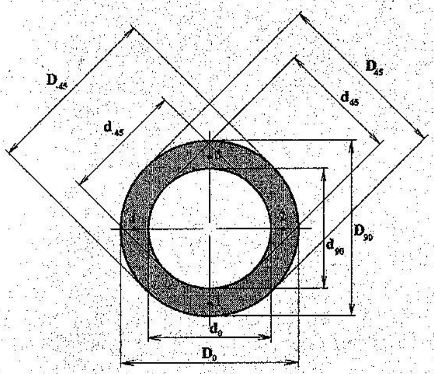
From the latter expression it follows that the error of CVG is inversely proportional to the Q-factor of the resonator and is directly proportional to the instability of internal friction. The value of ξ depends on a number of factors (for example, on the pressure variation inside the device), but its minimum value is determined by the instability of the structure of the material of the resonator. Therefore, CVG with quartz glass resonators will always have significantly better characteristics than devices with metal resonators, since their resonators have a much higher Q-factor and structural stability of the material. In spite of this, general-purpose mechanical resonators of general-purpose CVG are usually made of stainless steel to reduce production costs [3, 4]. The Q-factor of such resonators does not exceed $1 \cdot 10^5$, and the inhomogeneous intensity of internal friction in metals sharply reduces the stability of the characteristics of the sensing element and the CVG as a whole. This problem can be solved by using quartz resonators in low and medium precision CVG, however, the production of quartz resonators of known designs requires the use of precision mechanical equipment and complex production technology, which makes their use in such devices impossible due to high cost.

The aim of the work was to study a new design and a simple technology of manufacturing an inexpensive fused quartz resonator for general-purpose CVG. The basic idea is to manufacture such a resonator from a piece of commercially available fused quartz tubes. The assortment of such tubes produced by different firms is very wide, so the resonators can have a diameter that varies within wide limits. Since industrially produced quartz tubes have a small non-roundness, such resonators can be manufactured without additional mechanical processing of glass, i.e., without the use of precision mechanical machines. Although the quality of fused quartz in such tubes is inferior in impurity concentration to known brands of high-purity quartz glass, the Q-factor of such a "tubular" resonator is 5-10 times higher than that of metal resonators, and the high strength of the fused quartz structure provides high stability of its dissipative characteristics. The design of a tubular resonator can be quite simple. As a result, such a resonator has sufficiently high performance at low cost.

II. Results and Discussion

To test this approach, several samples of "tubular" resonators were made. We used tubes made of fused quartz with diameter of 20-30 mm of Russian and foreign production. The quality of fused quartz in such tubes can vary widely. To estimate the amount of impurities, we performed a spectral IR and UV analysis of the samples of the fused quartz tubes used. The content of impurities in the glass of imported pipes is much less, in addition, it completely lacks hydroxyl groups. This makes it possible to classify the material of Russian pipes as a widespread type II quartz glass, and import ones to pure quartz glass type IV.

The axial symmetry of the tubes was also different. Fig. 1 shows the data characterizing this parameter for some types of the tubes used.



Tube	Diameter, mm							
	D_0	d_0	D_{90}	d_{90}	D_{45}	d_{45}	D_{-45}	d_{-45}
Ø21	20.95	17.89	20.84	17.90	20,83	17,81	20,87	17,91
Ø31	31.15	28.22	31.19	28.33	31,17	28,00	31,24	28,32

Tube	Shell thickness, mm			
	Point 1	Point 2	Point 3	Point 4
Ø21	1.56	1.63	1.63	1.69
Ø31	1.38	1.33	1.52	1.62

Fig. 1. Evaluation of the axial symmetry of fused quartz tubes

It follows from the above data that the axial symmetry of fused quartz tubes can be quite high: for the imported sample studied, the deviation from the axial symmetry was about 20 μm.

From these tubes, we made several resonators of various designs (Fig. 2). Resonators were manufactured manually with the help of a glass blower. The fixing of the resonators is done by the foot (*A* and *B* in Fig. 2) or by the edge of the short part of the tube (*C* in Fig. 2).

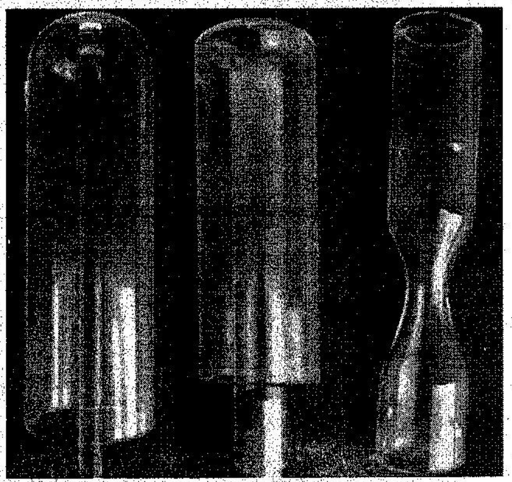


Fig. 2. Various designs of resonators from quartz tubes: *A* – with a solid stem; *B* – with a hollow stem; *C* – with a waistline.

The Q-factor of the resonators was measured by the decay time of free mechanical vibrations. The method of such measurements is described in detail, for example, in [5]. In Table 1, some of the measured parameters of these resonators are presented.

TABLE I. CHARACTERISTICS OF TUBULAR RESONATORS

Design	Material	Natural frequency of the 2nd form of oscillations, Hz	Natural frequency splitting, Hz	Q-factor	Q-factor dis-balance, %
A	Ø31 (RF)	4700	12	220000	2.6
B	Ø21 (RF)	11070	35	413000	3.2
C	Ø21 (RF)	11000	50	453000	1.1
C	Ø23 (USA)	13475	7	1022000	6

It can be seen that the Q-factor of tubular resonators, despite the simplicity of design and manufacturing technology, is quite high. The high splitting of the natural frequency is associated with the non-roundness of the original fused quartz tube, with the error of glass-blowing work performed manually, during the formation of the resonator, and also because of the errors in the length of the resonator from the tube. If some uncomplicated mechanical devices are used in this process, the axial symmetry of the tubular resonator can be significantly improved.

Due to the fact that the tube length L is relatively large, i.e., $L(R\delta)^{-1/2} \approx 20 >> 1$, the results of measuring natural frequencies f_n are in a good accordance with theoretical estimations [6] and relatively close to the corresponding natural frequencies of elastic ring oscillations [8]:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{\eta\beta^4 + \kappa^2 n^4 (n^2-1)^2}{n^2(n^2+1)}},$$

where n is the number of the form of oscillations;

$$\eta = \frac{E}{\rho R^2(1-\nu^2)}, \quad \beta \approx 1.875R/L, \quad \kappa^2 = \frac{h^2}{3R^2}\eta;$$

$E = 7 \cdot 10^{10}$ Pa is the elastic modulus; $\rho = 2.5 \cdot 10^3$ kg/m^3 is the material density; R, δ are the radius and the thickness of the shell; $\nu = 0.17$ is the Poisson's ratio.

The Q-factor of tubular quartz resonators is many times larger than that of metallic ones, which makes it possible to create an inexpensive general-purpose CVG with good performance. The most technological design if the variant with waistline. As the finite-element model shows, for the well-chosen dimensions of the working part, liner and waistline, there are practically no oscillations in the fixing plane, which allows achieving a high Q-factor of the resonator even with considerable axial asymmetry of the structure (Fig. 3).

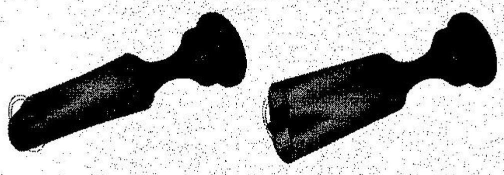


Fig. 3. Finite-element simulation of oscillations with respect to the 2nd form

III. BALANCING

The main disadvantage of tubular resonators is the large splitting of the natural frequency. This defect can be eliminated by balancing the resonator. The resonator mass distribution with respect to the circumference angle can be represented as a Fourier series as:

$$M(\varphi) = M_0 + \sum_{k=1}^{\infty} M_k \cos k(\varphi - \varphi_k),$$

where M_0 is the uniformly distributed mass of the resonator along the circumference angle; M_k is the value of the k-th form of the mass defect of the resonator; k is the number of the form of the mass defect of the resonator; φ_k is the orientation of the k-th form of the mass defect of the resonator relative to the conventional zero of the circumferential angle.

The different from zero amplitudes M_1, M_2, M_3 lead to oscillations of the center of mass of the resonator during the operation of the gyroscope, the scattering of the resonator energy in the places of its fixation, and to the systematic error of the CVG [7]. The splitting of the natural frequency arises at $M_4 \neq 0$ and leads to random errors of the CVG.

When balancing the general-purpose CVG resonators, as a rule, they are limited only by eliminating the splitting of the natural frequency, and the effect of vibration of the center of mass of the resonator is compensated by the use of various kinds of shock absorbers. Ion-plasma technology is often used to remove the mass defect of precision quartz resonators [8]. This technology provides high accuracy, but because of low performance it is suitable for balancing resonators with a small value of M_4. Therefore, in our case, it is advisable to carry out balancing in two stages. At the first stage, by one method or another, the difference between the natural frequencies of the resonator is reduced to 0.5-1 Hz, and the exact balancing of the resonator is carried out by ion-plasma technology as a part of the collected sensor element. Preliminary balancing is performed, for example, by the chemical method of removing the unbalanced mass from the surface of the working part of the resonator (Fig. 4).

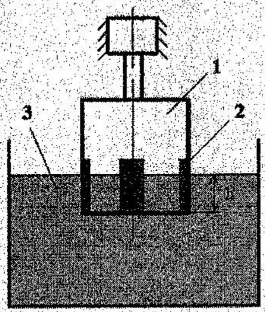


Fig. 4. The chemical method of removing the unbalanced mass from the surface of the working part of the resonator: *1* – resonator; *2* – protective mask; *3* – etching solution

Chemical dissolution of the glass is carried out in a solution of hydrofluoric acid or a solution of its salts in sulfuric acid [9]. The working edge of the resonator is protected in four places by an acid-proof mask, the amount of removed material is determined by the depth of immersion of the resonator h and the etching time. Another variant of etching involves inclined immersion of a cylindrical resonator in an etching solution [10].

IV. CVG Design

The structural appearance of a CVG constructed on the basis of a tubular resonator can differ depending on the methods of excitation and detection of oscillations. To maintain the high Q-factor of the resonator, it is expedient to use the electrostatic method, well known in gyroscopy. A variant of this CVG is shown in Fig. 5.

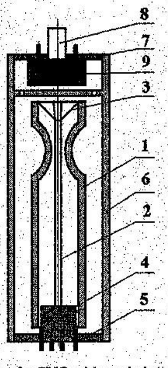


Fig. 5. A constructive version of a CVG with a tubular resonator.

The resonator *1* with an internal metallic coating is fixed by a conductive glue with a metal stem *2* through an elastic element *3*. The natural frequency of such a suspension of the resonator is selected in the range 0.5-1.5 kHz to ensure vibration isolation of the resonator and the housing *6*. This allows to sharply reduce the effects of vibration of the center of mass of the resonator caused by 1-3 forms of mass defect. The other end of the stem *2* is pasted into the pickoff *4*, electrodes connected to the hermetic leads are placed on its side surface *5*. The collected sensor element is subjected to precise balancing by the ion-plasma method and then installed in a sealed housing *6*. On the cover *7* of the upper compartment of the housing *6* a getter pump *9* is located with built-in electric heater and pumping out of the shtengel *8*. Installation of the assembled CVG is carried out with the help of shock absorbers, which reduce the pendulum oscillations of the resonator under external vibration. The control system of such a CVG does not differ from those described in the literature [8].

V. Conclusion

The general-purpose CVG resonator can be made from a segment of an industrial-manufactured fuzed quartz tube using the simple technology. The Q-factor of such a resonator reaches $1{\cdot}10^6$, with a variance of several percent. Such a resonator has a high stability of dissipative characteristics, which makes it possible to significantly improve the accuracy of general-purpose CVGs without increasing their cost price.

References

[1] D. Lynch, "Vibratory gyro analysis by the method of averaging," Proc. of The 2nd St.-Petersburg Int. Conf. on Integrated Navigation Systems, St.-Petersburg, 1995, pp. 26-34.

[2] D. Lynch, "Coriolis vibratory gyros," Proc. of The Symposium on Gyro Technology, Stuttgart, 1998, pp. 1.0-1.14.

[3] B.S. Lunin, M.A. Basarab, V.A. Matveev, A.V. Yurin, and E.A. Chumankin, "Resonator materials for Coriolis vibratory gyroscopes," Proc. of The 22nd St.-Petersburg Int. Conf. on Integrated Navigation Systems, Saint-Petersburg, 2015, pp. 379-382.

[4] Innalabs®, URL: http://www.innalabs.com/en/products/gyroscopes/.

[5] B.S. Lunin and S.N. Torbin, "Internal friction in quartz glass at moderate temperature," Moscow University Chemistry Bulletin, 2000, v. 41, no. 2, pp. 93-94.

[6] V.V. Novozhilov, The theory of thin shells, P. Noordhoff, Enlarged 2nd edition, 1964.

[7] N.E. Egarmin and V.E. Yurin, Introduction to the theory of vibratory gyroscopes, Moscow: Binom, 1993.

[8] B.S. Lunin, V.A. Matveev, and M.A. Basarab, Volnovoi tverdotelnyi giroskop. Teoriya i tekhnologiya (Solid-state wave gyroscope. Theory and technology), Moscow: Radiotekhnika, 2014.

[9] O.L. Altakh and P.D. Sarkisov, Shlifovanie i polirovanie stekla i stekloizdelii (Sanding and polishing glass and glassware). Moscow: Vysshaya shkola, 1988.

[10] M.A. Basarab, B.S. Lunin, V.A. Matveev, and E.A. Chumankin, "Balancing of hemispherical resonator gyros by chemical etching," Gyroscopy and Navigation, 2015, v.6, no.3, pp. 218–223.