Quartz Cylindrical Resonators for Mid-Accuracy Coriolis Vibratory Gyroscopes

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***Abstract*—Design and simple manufacturing technology of inexpensive quartz resonators for Coriolis vibratory gyroscopes (CVGs) of medium and low accuracy are proposed. The resonators are made from a piece of a commercially available fused quartz tube. The proposed technology makes it possible to produce such resonators without the use of precision machining, while the quality factor of such a resonator in the kilohertz frequency range reaches 1,000,000. Although this quality factor is much lower than that of precision quartz hemispherical resonators, it considerably exceeds the Q-factor of metal cylindrical resonators. In addition, the stability of the dissipative characteristics of the new resonators is also significantly increased. On the whole, this reduces the systematic drift of the device and its instability. These advantages of the new resonators allow us to significantly increase the accuracy of CVGs for inertial systems of medium and low accuracy without increasing their cost price. The report presents the designs and characteristics of such resonators, the methods of their balancing, as well as the possible constructive appearance of CVGs based on such resonators.**

Keywords—Coriolis vibratory gyroscope; fused quartz

I. Introduction

In recent years, Coriolis vibratory gyroscopes (CVGs), whose functioning is based on the precession of elastic standing waves in thin-walled mechanical resonators under the influence 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 can be evaluated.

As for other types of gyroscopes, the errors of CVGs are determined by defects of various kinds. In particular, CVGs has a significant systematic drift of a standing wave due to the inhomogeneity of internal friction in the resonator.

According to [1, 2], the amplitude of the velocity of this drift is

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

where θ is the orientation of the wave pattern in the resonator; f is the oscillation frequency; Q_1 and Q_2 are resonators Q-factors the along its intrinsic 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) is determined by the stability of the difference between two values of the internal friction. The higher values of Q_1 and Q_2 are, the easier procedure of ensuring the stability of the systematic drift of the CVG is, therefore, materials with low-volume internal friction and small thermoelastic losses are used for the production of resonators.

In [3], the possibility of using various materials for the production of CVG resonators is considered, including fused quartz, silicon, sapphire, stainless steel, and aluminum alloys. The calculations have shown that for the production of high-Q resonators (with Q-factor up to $10^6 \ldots 10^7$), the only suitable structural material is fused quartz, which has a low level of all types of internal friction and a stable structure. All other materials have either large internal friction or large thermoelastic losses. However, the production of quartz resonators requires the use of precision mechanical equipment and complex production technology, which makes their cost price high, and their use is therefore limited to use in expensive navigation equipment.

In order to reduce the cost of CVGs intended for use in the inertial systems of medium accuracy, mechanical resonators are usually made of stainless steel [4]. The Q-factor of such resonators does not exceed 10^5, in addition, the inhomogeneous intensity of internal friction in metals sharply reduces the stability of the characteristics of the sensitive element and CVG as a whole. As a result, the accuracy of the CVG based on metal resonators is not high, and it cannot be improved without a significant increase in the cost price.

The aim of this work was to develop a new inexpensive design of the fused quartz CVG for inertial systems of medium accuracy with the use of simple production technology. The use of fused quartz as a structural material allows us to increase several times the Q-factor of the resonator and to increase significantly the stability of its properties. The main purpose of the work is to manufacture such a resonator from a segment of an industrial-grade fused quartz tube. The assortment of such

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tubes produced by different firms is very wide, so the resonators can have a diameter that varies within wide limits. Since commercially available fused quartz tubes have a small non-roundness, such resonators can be manufactured without additional mechanical processing of fused quartz using precision mechanical machines. Although the quality of fused quartz in such pipes is inferior in impurity concentration to known brands of extremely pure silica, the quality factor of this “tubular” resonator turns out to be from 5 to 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. Design and Technology

Several samples of “tubular” resonators were fabricated. As a material, inexpensive tubes of fused quartz with diameter of 20-30 mm were used. The design of some resonators is shown in Fig. 1. Resonators were produced with the help of an oxygen burner, a mechanical circular saw was used to cut the resonator from the original quartz tube.

The quality of the resonators was measured by the decay time of free mechanical vibrations. The technique of such measurements is described in detail, for example, in [5]. Table 1 lists some of the measured parameters of these resonators. It can be seen that the Q-factor of “tubular” resonators, despite the simplicity of design and manufacturing technology, is quite high.

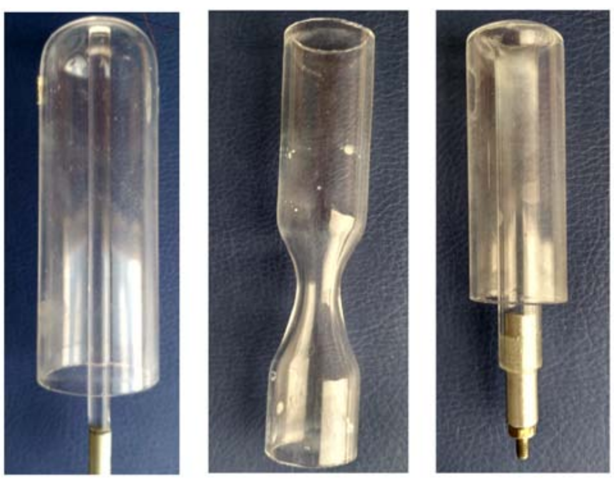

Fig. 1. “Tubular” resonators of various designs.

TABLE I. Characteristics of Fused Quartz Tube Resonators

Design	Diameter of the tube, mm	Working frequency, Hz	Frequency splitting, Hz	Q-factor	Q-factor split, %
A	32.5	4700	12	220000	2.6
B	23.0	13475	7	1022000	6.0
C	20.7	11070	35	413000	3.2

The high splitting of the natural frequency is associated with the non-roundness of the original quartz tube, with the error in the glass-blowing work performed manually, with the formation of the resonator, and also because of the errors in the length of the resonator from the tube. When even uncomplicated mechanical devices are used in this process, the axial symmetry of the “tubular” resonator can be significantly improved. If it is necessary to achieve high axial symmetry of the cylindrical shell, then it is possible to recommend turning such a resonator on a precision mechanical machine tool.

III. Balancing

One of the mandatory technological operations necessary for the production of CVG resonators is the balancing. The deviation of the geometry of the resonator from an ideal axisymmetric shape leads to the appearance of a mass imbalance, which is the source of the gyro error. The distribution of the resonator mass along the circumference angle can be represented as a Fourier series as

$$M(\varphi) = M_0 + \sum_{k=1}^{\infty} M_k \cos k(\varphi - \varphi_k), \qquad (2)$$

where k is the number of the form of the mass defect of the resonator; 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; 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.

As is known [6], the difference of M_1, M_2, or M_3 from zero leads to oscillations of the center of mass of the resonator during the operation of the gyroscope, additional dispersion of the resonator cavity energy in the places of its fixation, and to the systematic error of the CVG. When $M_4 \neq 0$, there is a splitting of resonator's natural frequency, which leads to random errors of the CVG. To eliminate the mass imbalance, the resonator is balanced with respect to these four forms of mass defect, i.e., the parameters M_1, M_2, M_3, M_4 and $\varphi_1, \varphi_2, \varphi_3, \varphi_4$ are determined and the unbalanced mass is removed.

When balancing the CVG resonators for inertial systems of medium and low accuracy, as a rule, they are limited only by eliminating the splitting of the natural frequency. The effect of vibration of the center of mass of the resonator in this case 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 [7]. Despite the high accuracy, this technology is too expensive to be used in mass production. In this case, for example, a chemical method can be used to remove an unbalanced mass from the surface of the working part of the resonator, which is obliquely immersed in an etching solution [8-10].

IV. Excitation of Oscillations

The constructive appearance of a CVG constructed on the basis of a “tubular” resonator can be different, depending on the methods of excitation and registration of oscillations. The electrostatic method, which is well known in CVG technology, allows us to fully preserve the Q-factor of the resonator, but requires the use of high-quality electronics, precision assembly of the device, and the provision of a high vacuum throughout the life of the CVG. It is much simpler and more technologically to realize the excitation and measurement of oscillations of the CVG resonator using piezoelectric sensors and actuators. In this case, the piezoceramic elements are glued (soldered) to the surface of the resonator in certain places. Preliminarily, a thin metal film is applied to these parts of the surface, serving as a "ground" for all used piezoelements.

The complexity of using piezoelements for a fused quartz resonator lies in the difficulty of finding the location of their installation, since the Q-factor of the sensor depends significantly on this. One can consider the construction of an excitation device and the removal of information using a non-contact electromagnetic system. A variant of the angular velocity sensor based on a quartz tube using an electromagnetic system is shown in Fig. 2.

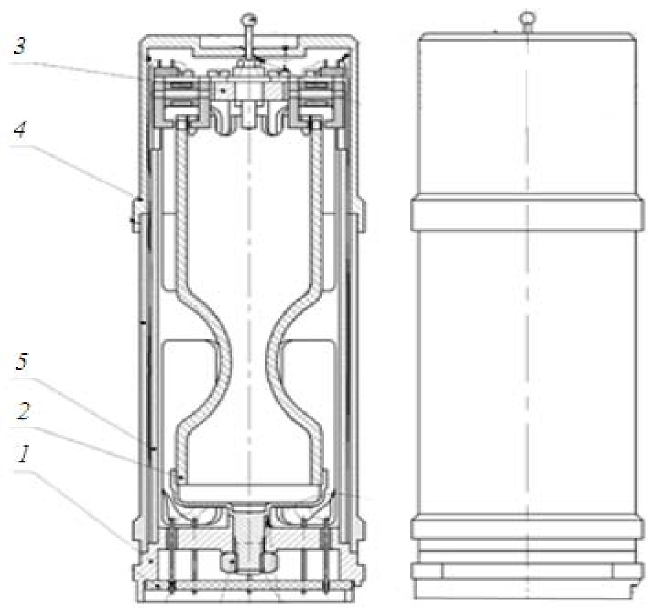

Fig. 2. Angular velocity sensor based on a quartz tube, using an electromagnetic system: *1*-base, *2*-fused quartz resonator, *3*-electromagnetic system, *4*-housing, *5*-cap.

Despite some complication of the design as a whole, there will not be a significant increase in labor intensity, due to the lack of strict assembly tolerances.

V. CONCLUSION

It was shown that CVG resonators for inertial systems of medium accuracy can be made from a segment of an industrial-manufactured fused quartz tube using simple technology. The Q-factor of such resonators reaches $5 \cdot 10^5$, with a variance of several percent. Such resonators have a high stability of dissipative characteristics, which makes it possible to significantly improve the accuracy of CVG without increasing its cost price.

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