Method for measuring voltages in channels of a hemispherical resonator gyroscope with an arbitrary orientation axes

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ABSTRACT

The article deals with issues related to solid wave gyroscopes, which are used as a sensor in inertial navigation systems. The article considers a variant of solving problem, when oscillations of the resonator are excited in directions that coincide with their own axes, oriented a priori is unknown. The main contribution this article is the method is proposed for measuring signal amplitudes in virtual main and quadrature channels, the orientation of which does not coincide with the orientation of the signal pickup electrodes. This is achieved by modeling algorithms for measuring the slope of the resonator's own axes and signal amplitudes in virtual channels are evaluation. In order to verify the adequacy of the proposed models simplified calculation formulas for programming microcontrollers are presented. An estimate of the error due to the use of simplified formulas is made. It is assumed that the use of this method will reduce the requirements for the quality of balancing the resonators of gyroscopes. The findings will be useful for mass production of navigation systems with gyroscopes, which have a small drift and are capable of experiencing large shock linear accelerations, for example, in underground inclined drilling, and in meteorological rockets.

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1. INTRODUCTION

One of the important promising directions in the development of civilian navigation systems is the use of gyroscopic angle sensors and angular velocity sensors based on solid-state wave gyroscopes, also called hemispherical resonator gyroscope (HRG). Such sensors can be used, for example, to measure the angular coordinates of a drill in inclined underground drilling. Currently, the production of HRG requires labor-intensive and complex balancing of a hemispherical resonator using equipment that costs more than $1 million. This significantly limits the possibility of mass production of navigation systems at HRG [1], [2]. To date, to ensure high-quality operation of the HRG, it is necessary to balance the resonator and then precisely match the spatial position of the reading electrodes with the resonator's own axes [3].

The theory of construction of solid-state wave gyroscopes is based on the application of the well-known Bryan effect [4], [5], discovered in 1890. The effect consists in the precession of a standing wave in the resonator as it rotates around an axis perpendicular to the plane of the ring. There are known solutions to general problems of the theory of HRG for an elastic inextensible ring, for an elastic tensile ring [6]-[8] the equations of oscillations of an elastic spherically symmetric body are known with an analysis of the precession of standing waves in it and with an analysis of the precession of standing waves in a hemispherical shell [9]-[11].

With the widespread positional electrostatic method of resonator excitation [12]-[15], when several excitation electrodes are used, the generated standing wave, as a rule, turns out to be tied to the position of the resonator electrodes. The working wave process of the HRG is created at the second harmonic (m=2) [16]-[18], which is the lowest harmonic of natural elastic oscillations of the hemispherical shell. To measure the position of the precessing wave, capacitive or optical sensors are used [19]-[21], which form two channels for picking up signals. The reading of signals both with a constant polarization voltage U_0 of the partial reading electrodes and with high-frequency polarization was carried out in the study of a metal resonator. The usual simplified circuit for reading signals with a constant voltage, which was used in the experiments, is shown in Figure 1. In the future, regardless of the purpose of the HRG or as an angle sensor [22], or an angular velocity sensor, and regardless of the algorithm for further signal processing in the digital part of the equipment, the magnitude of the resonator oscillations is measured at the location of the signal pickup electrodes.

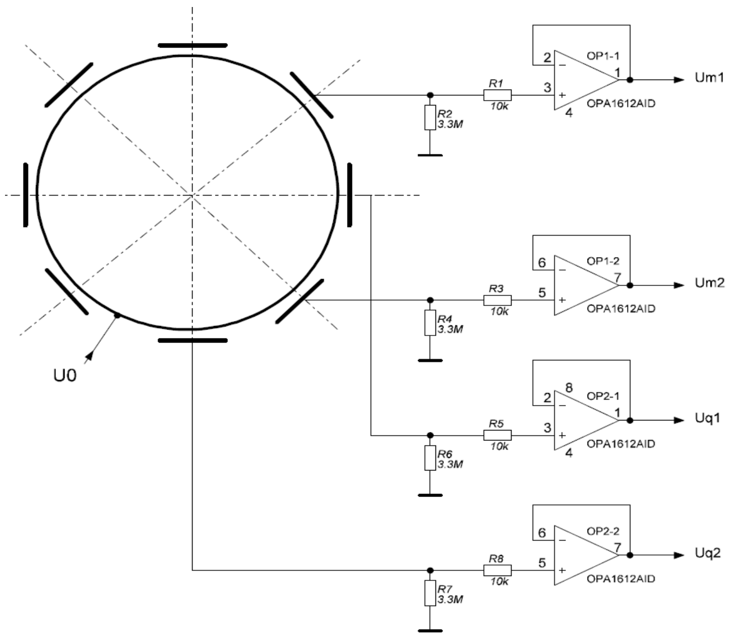

Figure 1. Simplified block diagram of the electrostatic read-out of signals

However, due to a violation in the manufacture of the axial symmetry of the resonator, own axes of the resonator are created with their own different frequencies. The position of two proper axes rotated between themselves by $\pi/4$. such that the natural oscillation frequencies of the resonator along each of these axes reach the largest and smallest values. Solving the problem of resonator balancing is a rather complicated and expensive [23]-[26] problem. Therefore, in some cases it may be of interest to use inaccurately balanced resonators. The main task of the work was to develop a method for measuring signals from the readout electrodes in HRG using unbalanced resonators with significant (several hertz or more) differences in natural frequencies. The novelty of the study lies in solving the problem of calculating readout signals for an arbitrary orientation of the readout electrodes relative to the own axes of an unbalanced resonator.

2. METHOD

The task was to recalculate the measured signals into signals of virtual main and buffer channels, coinciding with the own axes of the resonator. We assume that the resonator is excited in the second mode; we will approximately assume that the shape of the resonator is elliptical. Signal pickup electrodes form two channels for measuring voltages (Figure 2). The Figure 2 shows the measured mechanical vibrations in red. Vibrations in virtual channels are shown in blue, in which the corresponding signals need to be calculated.

We use the well-known ellipse equation in polar coordinates:

$$\rho = \frac{ab}{\sqrt{a^2 \sin^2 \phi + b^2 \cos^2 \phi}} \tag{1}$$

where a, b is the major and minor semiaxes of an ellipse; φ is the angle between the radius and the major semiaxis, this is the current polar coordinate; ρ is the radius length, distance from the center of the ellipse to the current point.

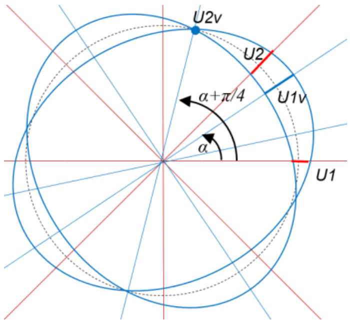

Figure 2. Standing wave orientation and measured signals

It is also known [1]-[8] that the magnitude of the signal taken in an oscillating resonator is proportional to the amplitude of mechanical oscillations Δ (Table 1).

Denote the resonator radius R. According to the results of measurements for a metal resonator, for example, given in [16], it is possible to estimate the value of the modulation coefficient $m = \frac{\Delta}{R}$, which can be observed in practice.

As shown in (2) for the amplitude the output signal [16]:

$$U_{1m} = \frac{m\omega C_0 (U_0 - U_{10})}{\sqrt{\frac{1}{R_1^2} + \omega^2 (C_0 + C_1)^2}} \tag{2}$$

where C_0=6 pF, the constant component of the sensor capacitance; m is the modulation coefficient; $\omega = 2\pi f$, f=1900 Hz is the own frequency of the resonator; C_1=3 pF is the parasitic capacitance; R_1=3…3,3 MΩ (R_2, R_4, R_6, R_7 on Figure 1); U_0 = 100 V.

Table 1. Mechanical oscillations amplitude

Duration of excitation, ms	1	2	3	4	5	6	7	8	9	10
Signal swing 1st channel $U_{1m\ p\text{-}p}$, mV	0.92	1.76	2.88	3.70	4.46	4.96	5.92	6.78	7.72	8.50
Amplitude in 1st channel, d_m, µm	1.72	3.29	12.4	6.92	8.34	9.27	11.1	12.7	14.4	15.9

For a metal resonator with a radius R=15 mm, the modulation coefficient was measured:

$$m = \frac{\Delta}{R} = \frac{(1.72 \ldots 15.9) \cdot 10^{-6}}{15} = (0.11 \ldots 1.06) \cdot 10^{-6} \tag{3}$$

if the modulation coefficient is sufficiently small, then in this case expression (1) can be simplified by successively setting:

$$a \approx R + \Delta; \quad b \approx R - \Delta; \quad \Delta^2 << R^2; \quad \left(1 - 2\frac{\Delta}{R} \cos 2\phi\right)^{-\frac{1}{2}} \approx 1 + \frac{\Delta}{R} \cos 2\phi.$$

then $\rho(\phi) \approx R - \Delta \cos 2\phi$.

In case of rotation of the ellipse by an angle, the length of the radius at the current point with the coordinate ϕ:

$$\rho(\phi, \alpha) \approx R - \Delta\, cos[2(\phi - \alpha)] \quad (4)$$

we number the channels and voltages. In the first read-out channel at $\phi = 0$, the measured amplitude of the signal voltage is proportional to:

$$U_1 = \Delta\, cos(2\alpha) \quad (5)$$

in the second read-out channel at $\phi = \pi/4$.

$$U_2 = \Delta\, sin(2\alpha) \quad (6)$$

How can one calculate the orientation of the two own axes of the resonator:

$$\alpha_1 = \frac{1}{2} arctg\left(\frac{U_2}{U_1}\right), \alpha_2 = \frac{1}{2} arctg\left(\frac{U_2}{U_1}\right) + \frac{\pi}{4}.$$

from (3) and (4) we obtain the signal amplitude $\Delta = \sqrt{\frac{2U_1U_2}{sin\, 4\alpha}}$.

Thus, it is possible to calibrate and more accurately estimate the orientation of the resonator's own axis α. If the resonator is rotated, its own axis will be oriented to an unknown angle β. Voltages in signal pickup channels will be measured:

$$U_{1\beta} = \Delta_\beta\, cos(2\beta),$$
$$U_{2\beta} = \Delta_\beta\, sin(2\beta).$$

in virtual channels oriented along the own axes of the resonator, the voltages:

$$\phi = \alpha + \frac{\pi}{4}, \quad U_{2V} = \Delta_\beta\, sin[2(\alpha - \beta)].$$

where $\beta = \frac{1}{2} arctg\left(\frac{U_{2\beta}}{U_{1\beta}}\right)$, $\Delta_\beta = \sqrt{\frac{2U_{1\beta}U_{2\beta}}{sin\, 4\beta}}$,

thus, according to the obtained formulas, it is possible to calculate the signal voltages in the virtual axes coinciding with the resonator's own axes, using the voltages taken from the arbitrarily oriented electrodes.

3. RESULTS AND DISCUSSION

In this section, it is explained the results of research and at the same time is given the comprehensive discussion experimental study of the influence of resonator nonideality on pickup signals. Investigations of oscillations that are excited in the main and quadrature channels are given. The process of energy transition from the main channel to the quadrature channel is estimated.

3.1. Experimental study of the influence of resonator nonideality on pickup signals

Visually, the excitation of a stationary metal resonator with unbalanced axes manifested itself in the appearance of beats, as shown in Figures 3-5. The figures are distinguished by different divisions along the time axis 100 ms/div, 1 s/div, 1 ms/div) respectively. Oscillations are excited in the main channel (upper, blue). The quadrature channel is shown in green (bottom). The resonator remained motionless. The figures show that there is an increase in the oscillation amplitude in the quadrature channel (green) simultaneously with a decrease in the signal amplitude in the main channel (blue).

Due to manufacturing errors of the resonator, the orientation of the excited standing wave does not coincide with the resonator's own axis. As a result, standing wave precession is observed. This is manifested in the amplitude modulation of voltages in the channels. The modulation frequency [27] is equal to the difference between the natural frequencies of the resonator axes, and for the studied metal resonator it was a few hertz. Figure 3 clearly shows the process of energy transition from the main channel to the quadrature one.

It is extremely difficult to analyze the rotation of the gyroscope under the observed voltage beats in the channels. Usually, the mismatch between the orientation of the natural axes of the resonator and the orientation of the standing wave is eliminated by expensive balancing. Consider a variant of signal processing from an insufficiently balanced resonator.

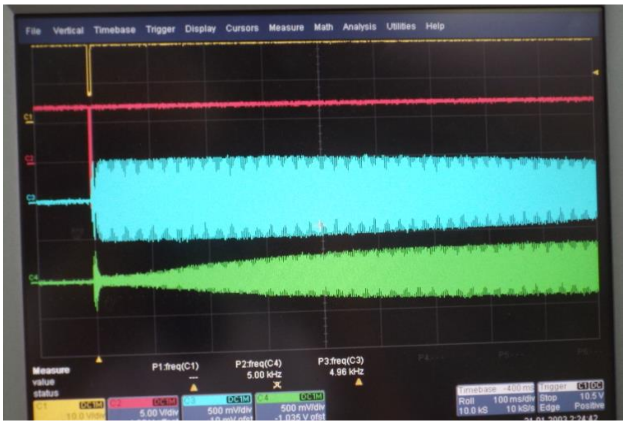

Figure 3. Oscillations are excited in the main channel (upper, blue). The quadrature channel is shown in green (bottom). The standing wave does not coincide with the resonator's own axis. Time division value 100 ms/div

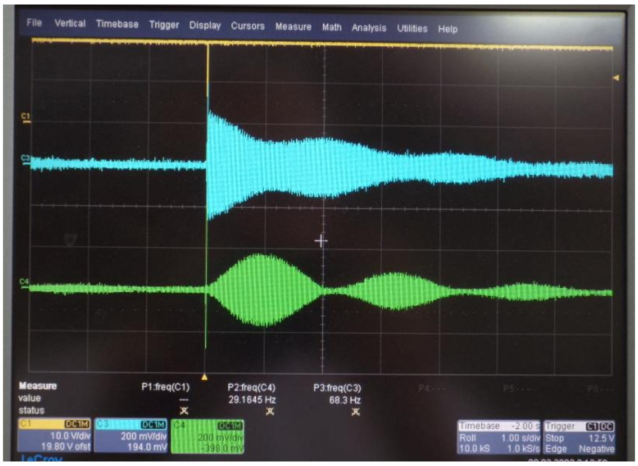

Figure 4. Voltage beats in the main and quadrature channels. Time division value 1 s/div

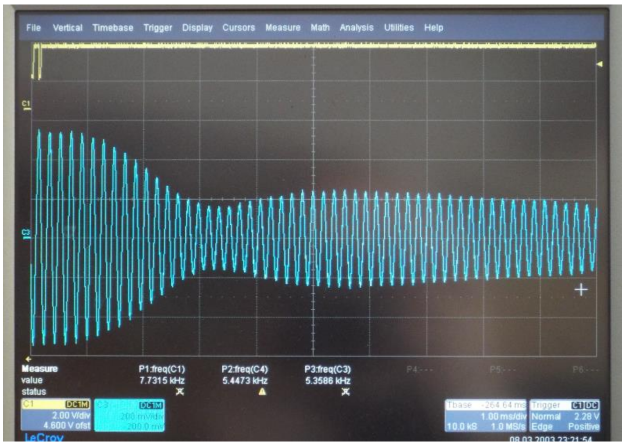

Figure 5. Fine structure of voltage beats in the main channel. Time division value 1 ms/div

3.2. Excitation of a standing wave coinciding with the orientation of the resonator own axes

Let us denote the own resonator axes X’-Y’, and the axes of signal pickup X-Y. Previously, in some works [7]-[11], it was proposed to excite a standing wave in a non-ideal resonator, initially rotated and oriented along its own axes X'-Y', and not along the axis of the excitation or pickup electrodes X-Y, as shown in Figure 6. A minimum of eight excitation electrodes must be used to shift the standing wave excitation. They need to be supplied with excitation voltages, adjustable in magnitude, so that the total excitation force forms oscillations along its own axis X’, the position of which is a priori unknown. Next, the signals of two channels were studied with a change in the amplitude and phase of the excitation pulses. The mutual position in space of the electrodes for picking up signals and excitation and their designations are shown in Figure 7.

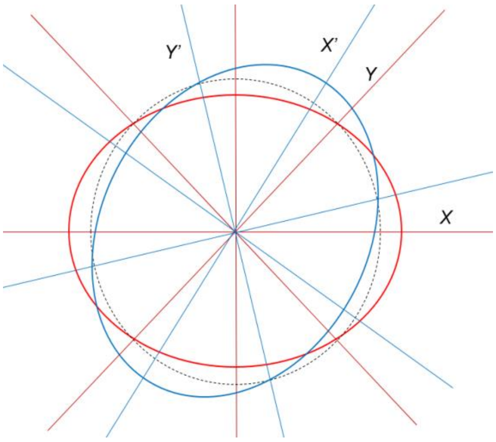

Figure 6. In the general case, the own axes of the resonator X'-Y' are shifted relative to the axes of signal pickup X-Y

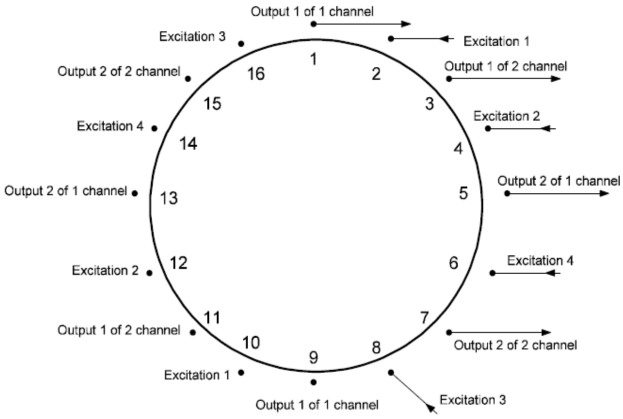

Figure 7. The position of the signal pickup and excitation electrodes

On Figures 8-17, the orientation of the standing wave generated in the direction of the excitation electrodes 2-10 and 6-14 is taken as zero. Accordingly, for the study, a complete rotation of the wave orientation by π/2, up to the direction of the electrodes 6-14 and 2-10, must be provided. It is obvious that a standing wave with orientation π/2 (Figure 16) is completely similar to a wave with orientation 0 (Figure 8). For the resonator under study, by more precise tuning near 6π/16, one can achieve the absence of observed beats in the channels (Figure 17). This indicates the coincidence of the intrinsic axis of the resonator and the orientation of the excited standing wave. We believe that in this case, virtual main (along its own axis) and quadrature (at an angle of 6π/16) channels are formed in the HRG, which coincide with the natural axes of the resonator. But in the general case, the orientation of these virtual channels does not coincide with the position of the signal pickup electrodes. Obviously, when the resonator is rotated, the voltages in the channels will change in accordance with the J. Bryan effect. For example, the picture shown in Figure 18 can be observed.

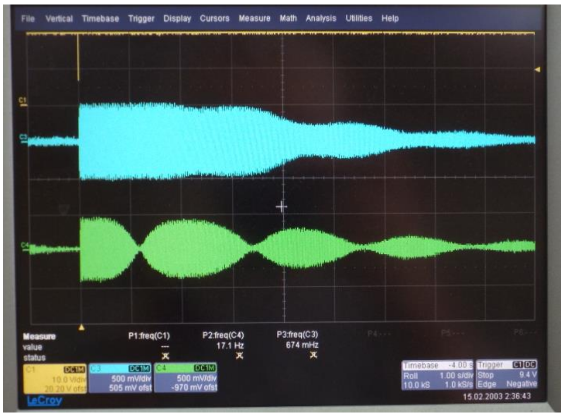

Figure 8. Orientation 0

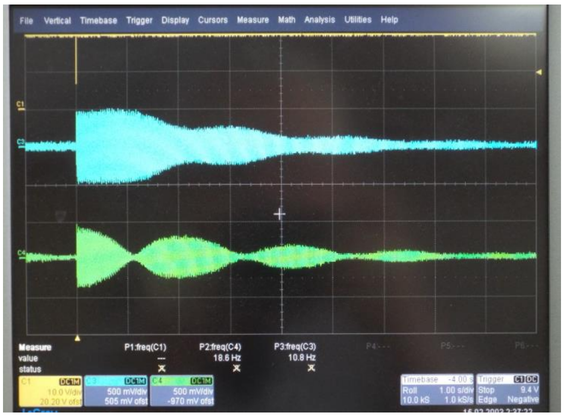

Figure 9. Orientation π/16

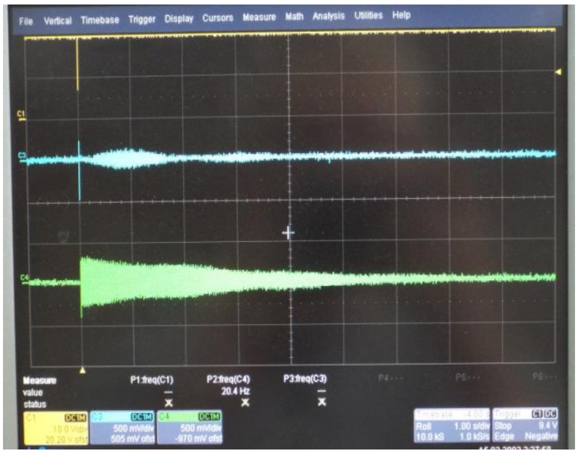

Figure 10. Orientation 2π/16

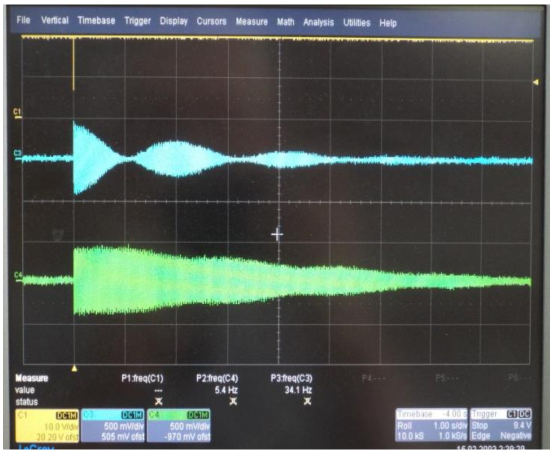

Figure 11. Orientation 3π/16

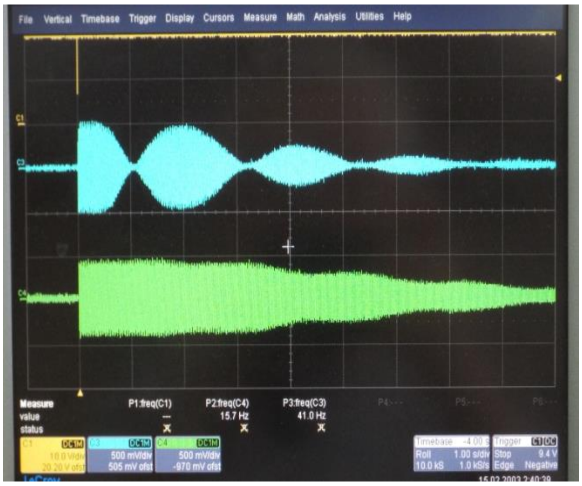

Figure 12. Orientation 4π/16

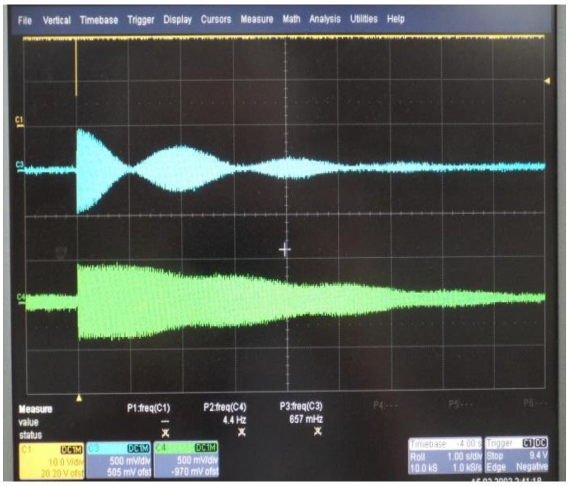

Figure 13. Orientation 5π/16

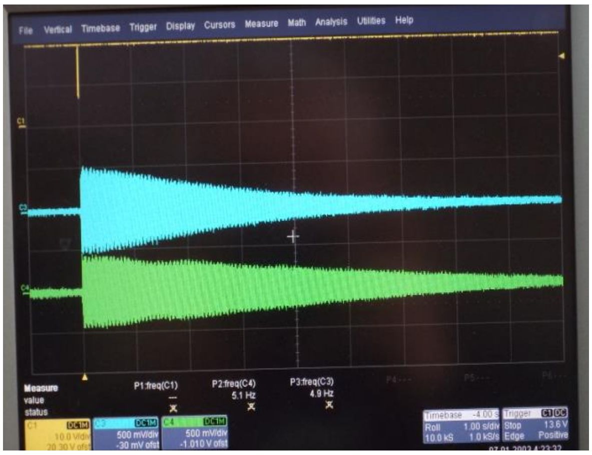

Figure 14. Orientation 6π/16

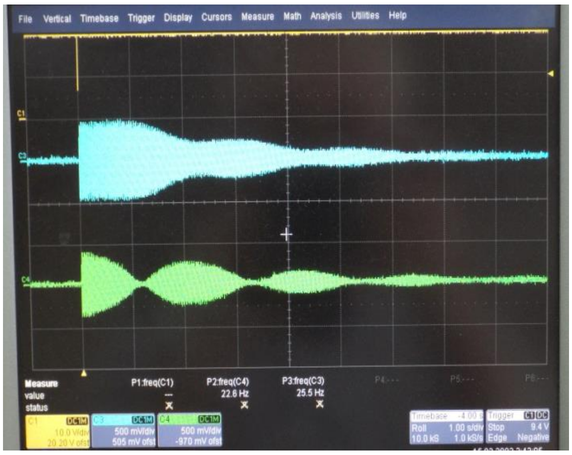

Figure 15. Orientation 7π/16

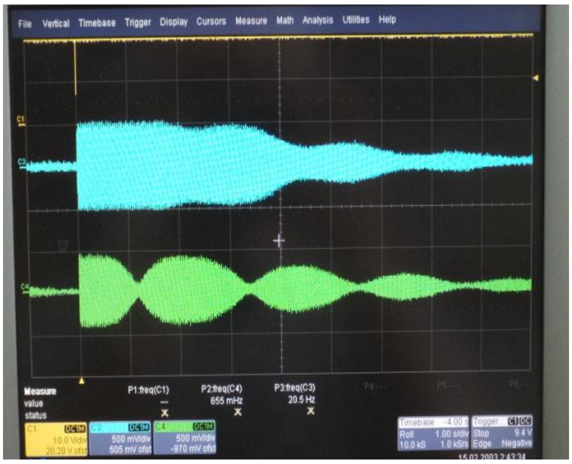

Figure 16. Orientation π/2

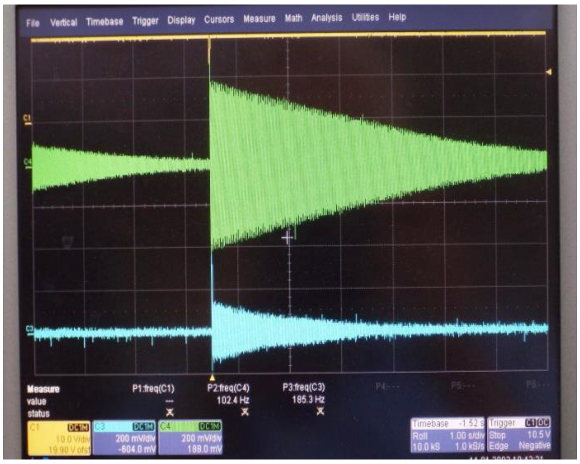

Figure 17. Excitation of a standing wave oriented along the own axes of the resonator

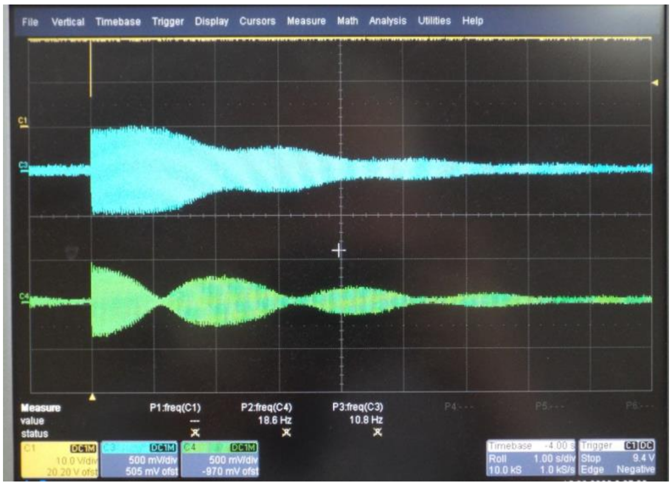

Figure 18. Typical signals in the channels when the resonator turns

4. CONCLUSION

Approximate formulas for measuring signal amplitudes in virtual channels oriented along the own axes of the resonator of a solid-state wave gyroscope are obtained in this work. Using these formulas, it is possible to calculate the orientation of the standing wave in the HRG and the angle of rotation of the wave due to the rotation of the gyroscope. This method can be used in a situation where the position of the signal pickup electrodes does not coincide with the orientation of the excited standing wave, for the case of using poorly balanced metal gyroscopes. Further direction of research can be directed to the development of a method for measuring the in-phase and quadrature components of oscillations in a virtual quadrature channel. The obtained novelty of the presented results consists in the proposed solution the problem of calculating reading signals for an arbitrary orientation of the HRG electrodes relative to the own axes an unbalanced resonator.

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