TRANSPORT SYSTEMS

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DESIGN ANALYSIS AND PARAMETERS CHOICE OF METALLIC CYLINDRICAL RESONATOR SENSOR FOR CORIOLIS VIBRATORY GYROSCOPE

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Abstract—*Two sensor designs of metallic cylindrical resonator Coriolis vibratory gyroscope are analyzed in this work. Resonant frequencies computer modeling results are presented and on their basis gyroscope sensor geometrical parameters choice is validated.*

Index Terms—Sensor; resonant frequency.

I. INTRODUCTION

To provide for a Coriolis vibratory gyro (CVG) high accuracy resonator should have the design that allows matching two mode of vibration (primary and secondary). In this case maximum sensitivity and accuracy can be reached. Besides, resonator should have axisymmetric geometry. There are two geometrical figures which have high axisymmetry: sphere and cylinder. Sphere or hemispherical shell has highest axisymmetry and on the basis of this shell it has been developed and produced fused quarts hemispherical resonator gyros (HRG) [1], [2]. These resonators have Q-factor of about 5-10 millions and are excited by electrostatic forces. Such resonators are not manufacturable and expensive in production, their mass balancing procedure is too complex and requires expensive equipment.

To increase manufacturability and to reduce production cost CVG resonator should be made of metal. However, metals have no high Q-factor and it can not be excited by electrostatic forces, which are too weak. Another perspective high force electrode, which has in addition high displacement sensitivity, is piezoceramic one.

Two sensor designs of metallic cylindrical resonator CVG with piezoceramic electrodes are analyzed in this work. Advantages and disadvantages of the two designs are considered, as well as metallic resonator parameters choice is carried out based on computer modeling of CVG sensor resonant frequencies.

II. PROBLEM STATEMENT

Analyze two CVG cylindrical sensor designs with sense and drive piezoelectrodes disposed on the bottom of the cylinder and on its wall from external mechanical disturbances point of view.

Choose sensor design parameters which minimize mutual influence of its components.

III. SENSOR WITH ELECTRODES ON ITS BOTTOM

Coriolis vibratory gyro sensor with electrodes glued on the bottom of cylindrical resonator is depicted in Fig. 1. If electrodes are glued on its vibrating portion, i.e. rim, resonator Q-factor would reduce some times (up to 10 times). Besides, piezoelectrodes can not be glued on round surface because of initial deformations and electric potentials arising in this case would have negative influence on CVG accuracy. Therefore, it is not expedient for metallic resonators to use hemispherical geometry, but cylindrical geometry where there is a flat bottom to glue piezo plates as electrodes.

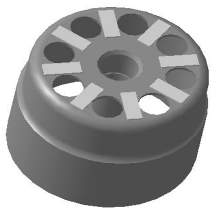


Fig. 1. Metallic cylindrical resonator with piezoelectrodes glued on the bottom [2], [3]

Sensor design in Fig. 1 has two main advantages. First is that electrodes are glued on the flat surface, second is that electrodes are located on the maximum far distance from the vibrating rim, hence, they have minimal impact on the resonator Q-factor. To increase vibration energy transfer to the bottom cylinder rim thickness relative to its rest lower portion should be provided. To reduce influence of stretching (tangential) forces from antinodes to nodes holes are performed to break mechanical connections between them in the places of electrodes location.

Resonator mounting unit on the sensor base is performed in view of cone-shaped design inverted inside the sensor as depicted in Fig. 2.

Resonator center of mass should coincide with its fixing point inside the cone. The base has protruding part, which end is performed as response cone-shaped figure to mount resonator on the base by conical mount method [4].

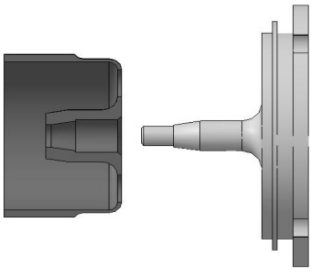


Fig. 2. Resonator conical mount on the base

Resonator material is elinvar steel which under special thermal processing can have high enough *Q*-factor and low frequency-temperature coefficient (5–10 times lower, than fused quarts) to use even in high grade CVG.

Resonator's rim sizes are chosen to meet the requirement of as far as possible frequency distance from maximum frequency of external disturbances which as a rule is 2000 Hz.

Lower portion of the cylinder thickness reduction results in reduction of its moment of inertia I_c, thus, results in reduction of requirements to manufacturing accuracy and to equality of elastic properties of spokes which piezo plates are glued on. This can be seen from the ratio of rim's moments of inertia I_r to I_c reduced to resonator's oscillation amplitude

$$\frac{I_c}{I_r} = \left(\frac{h}{H}\right)^2, \qquad (1)$$

where h is the cylinder lower potion thickness; H is the rim's thickness. So, when the following inequality $\frac{h}{H} \le \frac{1}{4}$ is valid requirements to manufacturing accuracy are reduced more than 10 times. High requirements to dimensional accuracy and elastic properties are imposed on resonator's rim only. This substantially increases resonator manufacturability and, hence, reduces cost.

Sensor's resonant frequencies calculation is performed with the aid of CAD ProEngineer. Sensor design and windows (holes) geometry are considered to be good if distance between resonant frequencies is more than 800 Hz.

To perform sensor modeling the following sensor's parameters have been taken: internal diameter is 23.6 mm and h = 0.4 mm. The rest parameters are presented in the table 1.

Resonators with different holes geometry are presented in Fig. 3.

Sensors resonant frequencies in the range of [1000–12000] Hz are presented in the table 2.

Sensors 2, 4, 6, 7 can be used to make CVGs.

However, this sensor design has disadvantages connected with that rim's oscillation amplitude is transferred to the bottom with coefficient of 0.05. It means that if rim's oscillation amplitude is 1 μm, then the bottom amplitude is 50 nm. As a result CVG sensitivity and accuracy is reduced. Besides, under external disturbances (vibrations and shocks) acting along CVG input axis, i.e. perpendicular to the sensor bottom, big load from the heavy, thicker rim is acting on the thin narrow spokes which electrodes are glued on. As a result of spokes deformation signals not connected with angle rate are provided to the electronics to process that causes CVG error.

TABLE 1

Coriolis vibratory gyro sensor's dimension

#	Ext. diam. mm	Rim's thick. mm	Rim's height мм	Cylinder height mm	Holes geometry
1	25	1.1	11	19	circle
2	25	1.1	11	19	triangle
3	25	1.1	10	17	circle
4	25	1.1	10	17	triangle
5	25.4	1.3	10	17	circle
6	25.4	1.3	10	17	triangle
7	25	1.1	9	15	circle
8	25	1.1	9	15	triangle

Fig. 3. Sensors with circle and triangle holes geometry

TABLE 2

Coriolis vibratory gyro sensors resonant frequencies

Sensor #1	Sensor #2	Sensor #3
F_1=1041.7 Hz F_2=2618.4 Hz **F_3=5163.5 Hz** F_4=5446 Hz	F_1=2160 Hz F_2=4168.4 Hz **F_3=5154.1 Hz** F_4=10736.8 Hz	F_1=1173.6 Hz F_2=2726.2 Hz **F_3=5277.3 Hz** F_4=5826.8 Hz
Sensor #4	Sensor #5	Sensor #6
F_1=1086.6 Hz F_2=2574.4 Hz F_3=5394.3 Hz F_4=**6096.5 Hz** F_5=11791.1 Hz	F_1=2117.3 Hz F_2=4092.9 Hz F_3=**6074 Hz** F_4=10376.2 Hz	F_1=1334.4 Hz F_2=2892.3 Hz **F_3=5440,6 Hz** F_4=6339.1 Hz
Sensor #7	Sensor #8	
F_1=2261.3 Hz F_2=4423.6 Hz **F_3=5263.9 Hz** F_4=11002.2 Hz	F_1=1100.1 Hz F_2=2400 Hz F_3=4756.1 Hz F_4=**5421.2 Hz** F_5=11432.6 Hz	

IV. SENSOR WITH ELECTRODES ON ITS WALL

To increase sensitivity and accuracy when measuring angle rate and to reduce sensitivity to external mechanical disturbances holes are performed on the cylinder wall. Spokes formed as a result of performed holes are ground to form flat surfaces to glue electrodes. The electrodes can be glued spokes sized, as depicted in Fig. 4, or spokes fraction sized. In the latter case electrodes can be glued in upper or lower potion of the spokes.

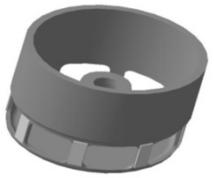


Fig. 4. Sensor with electrodes on its wall [4]

Relationship between rim's thickness and height, bottom and spokes thickness are chosen so that to minimize their mutual influences by their resonant frequencies separation.

Under external disturbances along axis of symmetry (gyro input axis) load is acting along spokes longitudinal axis in the design of Fig. 4 and along lateral axis in the design of Fig. 1. Spoke's stiffness along longitudinal axis is much more than that of along lateral axis. Really, let's suppose that in the designs of Figs. 1 and 4 spokes are equal sized rectangular beams, then the lateral spoke's stiffness K_x is

$$K_x = \frac{Ewh^3}{4l^3}, \qquad (2)$$

where E is Young's modulus of the spoke's material, w is spoke's width, h is spoke's thickness, l is spoke's length.

Longitudinal spoke's stiffness K_y is

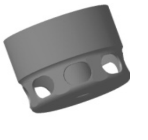
$$K_y = \frac{Ewh}{l}. \qquad (3)$$

For resonator diameter 25 mm, spoke's sizes can take the following values: $w = 3$ mm, $h = 0.4$ mm and $l = 6$ mm. In this case longitudinal stiffness is $K_y = 0.15E$ and lateral stiffness is $K_x = 7.4\times10^{-5}E$. Thus, longitudinal stiffness is more than lateral stiffness $K_y / K_x \approx 2\times10^3$ times. This results in substantially lower (2000 times) deformation amplitude under external mechanical disturbances for sensor design with electrodes on the wall, than on the bottom of the cylinder.

To model it has been developed sensor design of Fig. 4 with the following parameters: spoke's thickness is 0.5 mm, bottom thickness is 0.9 mm, rim's thickness 1.1 mm, rim's external diameter is 25 mm, rim's height is 11 mm. Sensors modeling results with different window (holes) configurations are presented in the table 3.

TABLE 3

Sensors resonant frequencies for different window and spoke sizes

Sensor #1  F_1=1951.7 Hz F_2=4103.7 Hz **F_3=5167,5 Hz** F_4=5352.2 Hz F_5=8928.5 Hz spoke's width 2 mm; window height 5.2 mm	Sensor #2  F_1=1998.9 Hz F_2=4222.5 Hz **F_3=5226.4 Hz** F_4=6013.3 Hz F_5=11121.7 Hz spoke's width 2 mm ; window height 5.2 mm
Sensor #3  F_1=2023.8 Hz F_2=4318.7 Hz **F_3=5238.1** Hz F_4=6070.3 Hz F_5=11371.2 Hz spoke's width 2 mm; window height 4.8 mm	Sensor #4  F_1=2034.9 Hz F_2=4283.4 Hz **F_3=5225.9 Hz** F_4=6123.1 Hz F_5=11565.4 Hz spoke's width 2.2 mm; window height 4.8 mm
Sensor #5  F_1=2048 Hz F_2=4311.4 Hz **F_3=5244.8 Hz** F_4=6182.8 Hz F_5=11933.6 Hz spoke's width 2.4 mm; window height 4.8 mm	Sensor #6  F_1=2169.9 Hz F_2=4421.2 Hz **F_3=5269.6** Hz F_4=5352.2 Hz F_5=8928.5 Hz spoke's width 2.2 mm; window height 4.8 mm

Sensors 2, 3, 4, 5 can be used to make CVGs, because these sensors have resonant frequency separation more than 800 Hz. As can be seen from the table 3 the windows in cylindrical sensors should be made oval, not square.

Seal's bushing is made of 29NiCo (kovar) alloy which temperature coefficient of linear expansion (TCLE) is equal to that of glass C52-1 (Russian classification) and equals 5.2×10^{-6} K^{-1}.

The base in which seal is glued is made of 44NiCrTAl with TCLE of 8×10^{-6} K^{-1}. Because reliable glass-wire seal junction is possible when TCLE of joint materials are close to each other, otherwise it results in cracks in the glass at temperature change and, hence, vacuum violation.

Use of 29NiCo material removes the TCLE problem for seal manufacture and allows not using glue and bushing in glass-wire seal junction that increase its reliability. Such base design is presented in Fig. 5.

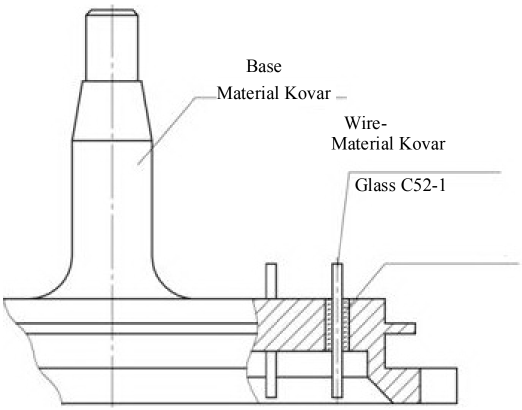


Fig. 5. Base design with glass-wire seal junction

In sensor design piezoceramic plates are glued along whole spoke's length. The wire is soldered to the lower portion of the plate and to the wireway. Sensor design is depicted in Fig. 6.

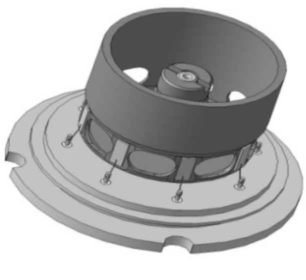


Fig. 6. Coriolis vibratory gyro sensor design

This design is covered by the cap and is welded at its base along the circle. In the upper side of the cap the hole is performed. Copper tube is soldered to this hole to pump out the air to make a vacuum inside the sensor. After vacuumization the tube is cut and soldered around.

V. Conclusion

Coriolis vibratory gyro metallic cylindrical sensor modeling results shown that the design with windows on the cylinder wall has advantages over that of with windows on the bottom. Use of sensor with window on the wall and conical mount on the base made of kovar will allow increasing CVG accuracy as well as reducing sensitivity to external mechanical disturbances.

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О. В. Петренко. Аналіз конструкції та вибір параметрів чутливого елемента коріолісового вібраційного гіроскопа з металевим циліндричним резонатором
Проаналізовано дві конструкції чутливого елемента коріолісового вібраційного гіроскопа з металевим циліндричним резонатором. Представлено результати комп'ютерного моделювання резонансних частот та на їх основі обґрунтовано вибір геометричних параметрів чутливого елемента гіроскопа.
Ключові слова: чутливий елемент; резонансна частота.

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А. В. Петренко. Анализ конструкций и выбор параметров чувствительного элемента кориолисового вибрационного гироскопа с металлическим цилиндрическим резонатором
Проанализированы две конструкции чувствительного элемента кориолисового вибрационного гироскопа с металлическим цилиндрическим резонатором. Представлены результаты компьютерного моделирования резонансных частот и на их основе обоснован выбор геометрических параметров чувствительного элемента гироскопа.
Ключевые слова: чувствительный элемент; резонансная частота.

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