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The GYTRIX Quartz Crystal Axisymmetric Mems GYRO: Preliminary measurements

Jean Guérard
DPHY

ONERA, Université Paris-Saclay
Palaiseau, FRANCE
jean.guerard@onera.fr

Maxime Duquesnoy
DPHY

ONERA, Université Paris-Saclay
Palaiseau, FRANCE
maxime.duquesnoy@onera.fr

Olivier Le Traon
DPHY

ONERA, Université Paris-Saclay
Palaiseau, FRANCE
olivier.le_traon@onera.fr

Pierre Lavenus
DPHY

ONERA, Université Paris-Saclay
Palaiseau, FRANCE
pierre.lavenus@onera.fr

Amandine Andrieux Ledier
DPHY

ONERA, Université Paris-Saclay
Palaiseau, FRANCE
amandine.andrieux@onera.fr

Raphael Levy
DPHY

ONERA, Université Paris-Saclay
Palaiseau, FRANCE
raphael.levy@onera.fr

Jeremy Bonhomme
DPHY

ONERA, Université Paris-Saclay
Palaiseau, France
jeremy.bonhomme@onera.fr

Abstract—On one hand tuning fork type open-loop quartz crystal MEMS gyroscopes achieve tactical - near navigation - grade performances through the excellent temperature and aging stability of quartz resonators, and the linear piezoelectric transduction. On the other hand, recent developments enable silicon based axisymmetric designs to achieve the same thermo-mechanical behavior of the two gyro modes, improving the bias and scale factor stabilities. They also enable matching the two frequencies and then increasing the scale factor in a force rebalance configuration. The axisymmetric quartz crystal MEMS gyro presented here benefits from the advantages of these two kinds of gyro. Its principle of operation as well as a first design and expected performances were reported; the performance objective of this new cell is to achieve a bias repeatability better than $0.1^\circ/\text{h}$ and an $\text{ARW} < 0.005^\circ/\sqrt{\text{hr}}$ in the closed loop configuration, as well as good immunity to vibrations and thermal variations. The eigen frequency and Q factor variation identity of the two gyro modes are key parameters enabling bias and scale factor stability, this paper reports the experimental validation of the thermomechanical behavior identity between the drive and sense modes of this new axisymmetric quartz crystal gyro. This is the first step towards a high performance quartz crystal closed-loop gyroscope.

Keywords—gyroscope, quartz crystal, MEMS

I. INTRODUCTION

The axisymmetric quartz crystal MEMS gyro presented here benefits from the advantages of tuning fork type open loop quartz crystal MEMS gyroscopes [1] and silicon based axisymmetric designs [2] [3] [4] [5]. Its principle of operation as well as a first design and expected performances were reported at INERTIAL2022 [6]. The performance objective of this new cell is to achieve a bias repeatability better than $0.1^\circ/\text{h}$ and an $\text{ARW} < 0.005^\circ/\sqrt{\text{hr}}$ in the closed loop configuration, as well as good immunity to vibrations and thermal variations.

The eigen frequency and Q factor variation identity of the two gyro modes are key parameters enabling bias and scale

factor stability. The Q factor is mainly limited by anchor losses and thermoelastic damping [7][8]. This paper reports the experimental validation of the thermomechanical behavior identity between the drive and sense modes of this new axisymmetric quartz crystal gyro.

II. MEMS DESIGN

A. Axisymmetric design

This sensor is based on a new concept, recently patented, and able to operate as an integrating gyro. This new device, called GYTRIX (GYro for TRIGonal piezoelectric Xtal), is specially designed for quartz crystal. As shown in figure 1, it involves a central mass, vibrating isotropically in the plane of the device, connected to a mounting part by means of three strictly identical link elements, positioned at 120° to each other around the central mass. These original link elements ensure at the same time a role of stiffness and inertial mass, allowing a perfect balance of the central mass momentum when vibrating in the plane of the device. The orientation of the link elements at 120° from each other was chosen to consider the trigonal symmetry of quartz and thus ensure a perfect similarity of mechanical and thermal properties of the three elements. As a result, two degenerated modes (same frequencies) are obtained with nominally exactly the same thermal behavior and the same quality factor.

The two points mentioned above give the gyro excellent temperature behavior. Indeed, the use of symmetrical and aligned modes on the underlying crystalline network allows obtaining a variation of the frequency and the quality factor according to the temperature strictly identical for the two modes, which is a critical point for gyro bias stability. Moreover, for the same reasons, the sensitivity of the scale factor with respect to the thermomechanical stresses generated by the packaging is theoretically zero.

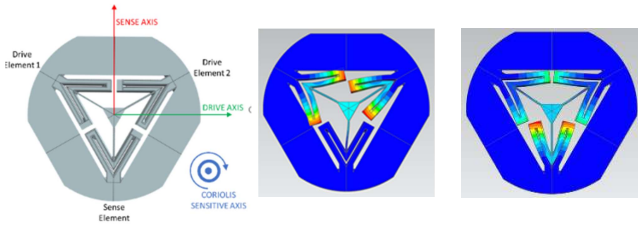


Figure 1: Gyro transducer model (left), Drive (center) and sense (right) modes.

B. Q factor optimization

1) Anchor loss

The decoupling of the resonator from its support is essential because it guarantees not only a very high quality factor but also excellent insulation of the resonator from external disturbances. To achieve this optimization, numerical simulations using finite element analysis are necessary. The objective is to quantify the proportion of energy E_{support} contained in the support of the resonator relative to the total deformation energy of the whole system E_{tot} . This makes it possible to determine the equivalent quality factor of the system according to the following equation:

$$Q_{\text{support}} = \frac{2\pi E_{\text{tot}}}{E_{\text{support}}} \quad (1)$$

The evaluation of Q_{support} makes it possible to give a lower limit to the quality factor linked to this dissipation mechanism, considering that all of the energy transmitted to the support is dissipated. As part of this study, the resonator support consists of six Kovar pads, linked to a base itself made of Kovar. A modal analysis is then carried out and the ratio between the deformation energy of the support pads and that of the total system is calculated. The structure is optimized to lower the anchor loss, and a related Q factor = 800.000 has been calculated.

2) Thermoelastic damping

The resonator vibrates mainly in flexural mode, the associated thermoelastic losses are well described by the Zener model [8] and more recently by the Lifshitz model [7]:

$$^{-1}_{hermo} = \frac{E\alpha^2 T_0}{C_p} \frac{6}{\xi^2} \left(1 - \frac{\sinh \xi + \sin \xi}{\cosh \xi + \cos \xi} \right)$$

with $\xi = e \sqrt{\frac{\omega_0}{2\chi}}$ (dimensionless), e the width of the beam, ω_0 the natural pulsation of the vibration mode, χ the quartz thermal diffusivity, E its Young's modulus, α the coefficient of thermal expansion, C_p its thermal capacity per unit volume and T_0 the average temperature.

We note that the thermoelastic quality factor depends on the width of the vibrating beam as well as its operating frequency. The thermoelastic damping Q factor can be calculated by FEM analysis to simulate the compressed heated fibers and

the stretched cooled fibers of the beam. The thermoelastic quality factor has been calculated as 200.000.

3) Total quality factor

The simulated total quality factor is:

$$Q_{\text{tot}} = 1 / \left(\frac{1}{Q_{\text{support}}} + \frac{1}{Q_{\text{thermo}}} \right) = 160.000$$

III. PROTOTYPE REALIZATION

In order to guarantee the isotropy of the stiffnesses and damping, the fabrication process of the gyro transducer must preserve the strict identity of the three link elements. As illustrated in the figure below, the machining is carried out by a hydrofluoric acid-based wet chemical etching, which generates identical etching facets on the three link elements thanks to the design following the quartz crystal axisymmetry. The link elements are thus nominally identical and the axisymmetry is preserved.

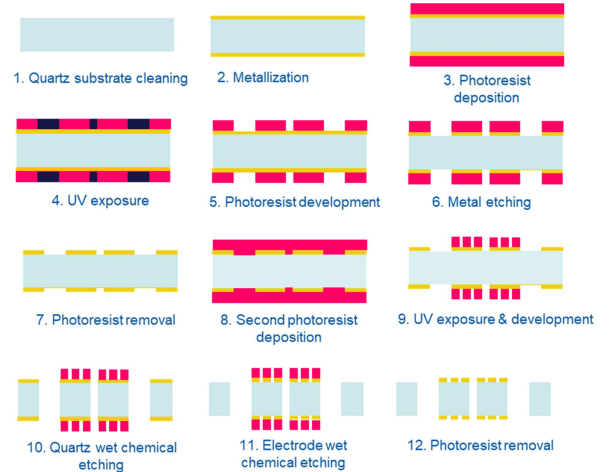


Figure 2: Wet chemical etching steps

A first design and realizations have been undertaken, as shown in figure below, and allowed to validate the identity of thermomechanical parameters of the two gyro modes.

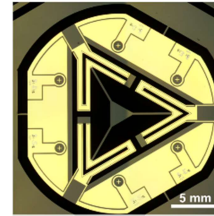


Figure 3: Quartz crystal gyro transducer manufactured by wet chemical etching

IV. EXPERIMENTAL RESULTS

MEMS gyros have been packaged under vacuum and integrated with charge amplifiers as front end analog electronics. A ZI-HF2LI is used to set a PLL oscillator loop to

keep the drive mode or the sense mode at resonance. Prototypes are then tested in a temperature chamber in the range from 0°C to 70°C. For each temperature step, the eigen frequencies of the two modes are measured as well as their Q factor by the ring down method. The results are shown in figure 3 and figure 4, the frequency difference variation is only 3000 ppm, thus a 3 times improvement compared to the previous quartz tuning fork gyroscope developed at ONERA that used a square section tuning fork, drive mode in plane and sense mode out of plane, and showed a variation of frequency difference over a 80 °C temperature range of 13.000ppm [9]. Q factor difference variation is only 5%, also a 2 times improvement from the previous quartz tuning fork gyro.

The measured Q factors are in line with the expected ones, confirming the excellent decoupling of the cell from the frame.

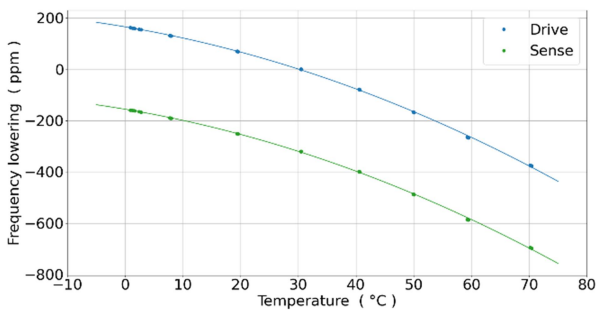


Figure 4: Drive and sense frequency relative drift over temperature.

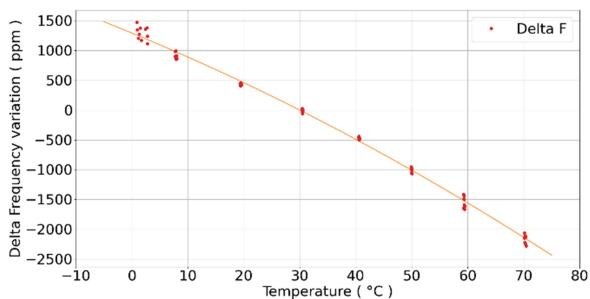


Figure 5: Frequency difference of the gyro modes relative drift versus temperature.

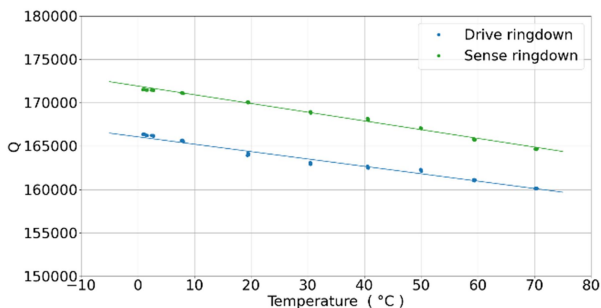


Figure 6: Q factor of drive and sense modes versus temperature.

V. CONCLUSION

First prototypes of a new quartz axisymmetric gyro have been realized, first test have been carried out and enable to validate the identity of the frequency and Q factor variation over temperature. The next step is to validate the gyro performances in terms of ARW, bias and scale factor temperature variations.

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