Analytical Modeling and Design Optimization of UV-LIGA based 4-DOF Vibratory Gyroscope

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Abstract

This paper presents analytical modeling and design optimization of structurally decoupled 4-DOF vibratory gyroscope with increased robustness and gain. The proposed design utilizes dynamic amplification in 2-DOF drive mode oscillator and 2-DOF sense mode oscillator to achieve large gain. Equations of motion are derived for the gyroscope using vector method and the same are verified by lagrangian dynamics. The equations are solved analytically both in frequency domain and time domain to obtain the device's characteristics. The design is optimized to meet the desired specifications and to be compatible with UV-LIGA fabrication technique having 10 μm thick nickel as structural layer. Sense mass displacement of 114.2 nm corresponding to the rotation induced coriolis force is calculated at actuation voltage of 40 V_{dc} and 20 V_{ac} with angular rate of 35 rad/s. Wide operation bandwidth of 690 Hz is achieved.

Keywords: MEMS, Gyroscope, Modeling, Optimization, UV-LIGA.

Introduction

In the conventional 2-DOF MEMS vibratory gyroscopes, the mode-matching requirement renders the system response very sensitive to variations in system parameters due to fabrication imperfections and fluctuations in operating conditions [1]. Recently new design approaches have been implemented utilizing multi-DOF with increased robustness to fabrication imperfections and environmental variations [2]-[4].

The proposed design of 4-DOF vibratory gyroscope provides inherent robustness by achieving large operational bandwidth. It utilizes dynamic amplification to achieve large oscillation amplitudes without resonance, while mechanically decoupling the drive direction oscillations from the sense direction oscillations. The prototyping of the device will be done using UV-LIGA [5] fabrication technique having 10 μm thick nickel as structural layer.

Analytical modeling

The lumped model of proposed design is shown in Fig. 1. The first mass m_1 and the combination of second and third masses (m_2+m_3) form 2-DOF drive direction oscillator, where m_1 is the driven mass. The second mass m_2 and the third mass m_3 form 2-DOF sense direction oscillator.

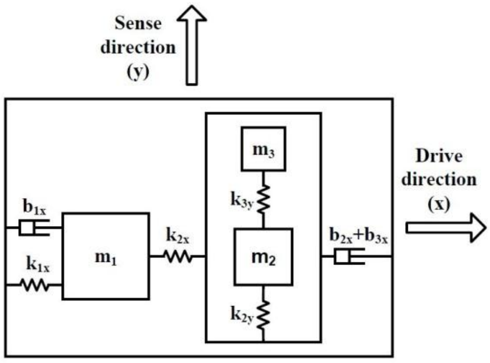

Fig. 1: Lumped mass-spring-damper model of overall 4-DOF vibratory gyroscope

The equations of motion (along the x-axis and y-axis) of the three mass system subjected to an angular rate Ω about the axis normal to the plane of motion (z-axis) in the inertial frame are derived using vector method and the same are verified by lagrangian dynamics. They can be expressed as:

$$m_1\ddot{x}_1 + b_{1x}\dot{x}_1 + k_{1x}x_1 = k_{2x}(x_2 - x_1) + F_d \quad (1)$$

$$(m_2 + m_3)\ddot{x}_2 + (b_{2x} + b_{3x})\dot{x}_2 + k_{2x}(x_2 - x_1) = 0 \quad (2)$$

$$m_2\ddot{y}_2 + b_{2y}\dot{y}_2 + k_{2y}y_2 = k_{3y}(y_3 - y_2) - 2m_2\Omega\dot{x}_2 \quad (3)$$

$$m_3\ddot{y}_3 + b_{3y}\dot{y}_3 + k_{3y}(y_3 - y_2) = -2m_3\Omega\dot{x}_3 \quad (4)$$

where, m_1, m_2, m_3 are masses; b_{1x}, b_{2x}, b_{3x}, b_{2y}, b_{3y} are damping coefficients; k_{1x}, k_{2x}, k_{2y}, k_{3y} are spring constants; $F_d=f_0 sin(\omega_d\ t)$ is electrostatic driving force having ω_d as driving frequency.

Finally, the equations (1)-(4) are solved analytically both in frequency domain and time domain to obtain the device's characteristics.

Design optimization

The objectives of design optimization are: to achieve large operational bandwidth both in drive and sense directions, to have sense direction capacitance change of the order of *fF* or more and the overall design should be such that it can be fabricated using UV-LIGA fabrication technique having 10 μm thick nickel as structural layer. For design optimization, expressions of frequency response and transient response are implemented in MATLAB and several iterations are carried out to fulfill the earlier mentioned objectives. Table 1 shows the summary of the design parameters for the optimized design.

Table 1: Summary of the optimized design parameters

Parameters	Optimized values
m_1	5.31×10^{-7} kg
m_2	1.8×10^{-7} kg
m_3	2.11×10^{-8} kg
k_{1x}	83.85 N/m
k_{2x}	38.37 N/m
k_{2y}	28.42 N/m
k_{3y}	3.33 N/m

Results and discussion

The analytical frequency responses of 2-DOF drive mode oscillator and the 2-DOF sense mode oscillator are shown in Fig. 2. Fig. 2(a) shows that two resonance frequencies of 2-DOF drive mode oscillator are located at 1.43 kHz and 2.79 kHz with a flat region between the peaks. Fig. 2(b) shows that two resonant frequencies of 2-DOF sense mode oscillator are located at 1.68 kHz and 2.37 kHz with a flat region between the peaks. The flat regions of drive and sense direction oscillators are also overlapping. The device can be operated in this common flat region providing the wide operation bandwidth of 690 Hz.

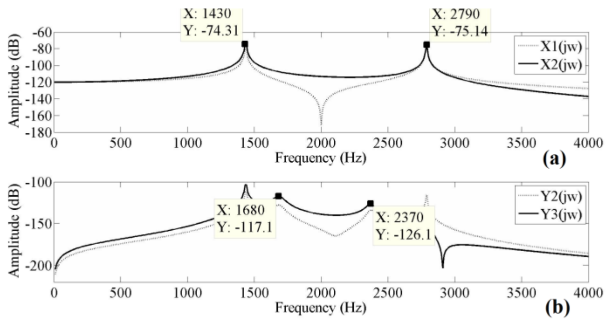

Fig. 2: Frequency response of (a) drive mode oscillator (b) sense mode oscillator

To analyze the response time as well as the detection amplitude of the gyroscope, analytical transient analysis is carried out at 40 V_{dc} and 20 V_{ac} with angular rate of 35 rad/s. Drive frequency is kept as 2 kHz. The results are shown in Fig. 3. It can be seen from Fig. 3(d) that the steady state amplitude of y_3 is 114.2 nm. Using the differential capacitance scheme capacitance change of 3.6 *fF* can be achieved in sense direction.

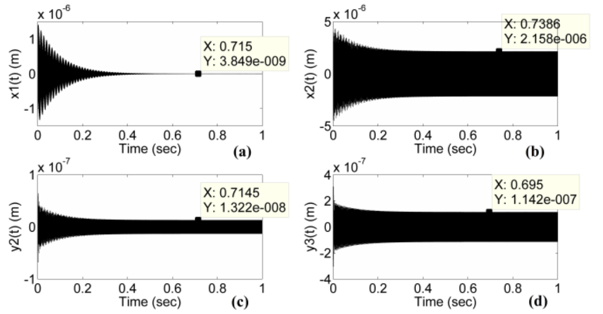

Fig. 3: Transient response of proposed gyroscope design: (a) $x_1(t)$ (b) $x_2(t)$ (c) $y_2(t)$ (d) $y_3(t)$

Conclusion

A 4-DOF vibratory gyroscope design concept with 2-DOF drive mode oscillator and structurally decoupled 2-DOF sense mode oscillator is presented. Equations of motion are derived for the gyroscope using vector method and the same are verified by lagrangian dynamics. The Equations are solved analytically both in frequency domain and time domain to obtain the device's characteristics. The design is optimized to meet the desired specifications and to be compatible with UV-LIGA fabrication technique having 10 μm thick nickel as structural layer. Sense mass displacement of 114.2 nm corresponding to the rotation induced coriolis force is observed at actuation voltage of 40 V_{dc} and 20 V_{ac} with angular rate of 35 rad/s. Wide operation bandwidth of 690 Hz is achieved.

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