A Novel Design of MEMS Gyroscope with Control Capability

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Abstract: High performance MEMS gyroscopes can be implemented by embedding in a closed loop controller. For these gyroscopes, the electrostatic controlled force on the proof mass is inherently nonlinear. This study reports a MEMS gyroscope with control capability in which comb drive electrodes are employed as the controlling mechanism to linearize the electrostatic controlled force. To avoid interaction of drive and control comb drive electrodes, another mass has been added to the structure. Consequently, proposed gyroscope consists of a 2-DOF sense mode oscillator and a 1-DOF drive mode oscillator. The prototype with an overall size of 0.46 × 0.635 mm is designed to be fabricated in surface Micromachining process with 3 µm structural layer thickness. The device operation has verified by Finite Element Method simulations showing a raw mechanical sensitivity of 32 nm for drive direction oscillation amplitude of 120 nm and angular rotation of 50 [°/s].

Keywords: MEMS gyroscope, closed loop controller, delta sigma modulator, 2-DOF oscillator.

1. Introduction

Dynamic range of MEMS inertial sensors such as accelerometers and gyroscopes are limited meaning that if the amplitude of input becomes larger than specific range, the output of the sensor would be nonlinear. On the other hand, small motion of the proof mass leads to small capacitive signal which limits the sensitivity of the sensor. Hence, embedding MEMS inertial sensors in a close loop controller that provides a small input and a high resolution interface circuit can be a solution for above mentioned problems[1].

Compared to open loop gyroscopes, closed loop architectures offer many advantages such as improving the linearity, dynamic range, bandwidth and robustness to fabrication imperfections and ambient variations. Therefore during the past few years, gyroscopes in a closed loop controller have become so attractive. Recently, a closed loop control strategy based on delta sigma modulator has been proven to be beneficial which provides a high resolution digital output without any excess analog to digital converter[2-4].

Several architectures have been reported to date for gyroscope in closed loop controller [2, 3, 5, 6]. In [2, 5] sensing and controlling electrodes have been configured separately, but in [3, 6] they have been shared by time-multiplexing. Implementation of separated electrodes is simple, however due to fewer number of sense electrodes, electrical sensitivity reduces. On the other hand, design of timing diagram in the multiplexed electrodes is sophisticated. In both of the previously published methods, parallel plate electrodes are used in order to apply controlling force on the proof mass. In that way, the significant problem is nonlinearity of the electrostatic controlling force which produces harmonics in power spectral density of delta sigma controller which in turn reduces the resolution.

In this paper, a designing strategy is put forward to eliminate nonlinearity effect and improve sensitivity which results in a structure including a 2-DOF (degrees-of-freedom) sense mode oscillator and a 1-DOF drive mode oscillator. This new design combines the robustness of a 2-DOF sense mode with the dynamic range improvement of a closed loop microgyroscope.

This paper is organized as follows; in section 2 a MEMS based gyroscope with control capability is proposed and operating principles are discussed. Section 3 expresses design procedure step by step. Section 4 demonstrates simulations results and finally section 5 gives the conclusion.

2. Proposed device structure and operating principles

Block diagram of a controlling system for MEMS gyroscope based on delta sigma modulator is shown as Fig. 1, where $A_0$ is the gain of the readout circuit that
converts the displacement to voltage and \( k_{fb} \) is the gain through the voltage to electrostatic force conversion on the proof mass. It is clear that \( G_s(s) \) embeds as loop filter of the delta sigma modulator.

As described in the introduction, controlling force in the previous works is nonlinear. Indeed, variable gap electrodes are frequently utilized in the sense direction of MEMS gyroscopes to obtain high sensitivity. In the case of separated sensing and controlling electrodes, some of sensing electrodes are appropriated for control purpose \([5, 6]\) and \( k_{fb} \) is given by

\[
k_{fb} = \frac{\varepsilon_0 A_{fb} V_{fb}^2}{2(d_0 + \text{sgn}(y(n)) x)}
\]

where \( \varepsilon_0 \) is the dielectric constant, \( A_{fb} \) is the area of the feedback electrode, \( V_{fb} \) is the feedback voltage, \( d_0 \) is the nominal gap of the sensing capacitor, \( x \) is the proof mass residual deflection and \( y(n) \) is the quantizer output bit stream assumed to be \(+1\) or \(-1\). Equation (1) denotes that controlling force is nonlinear relating to the proof mass residual deflection \( x \), and the Taylor expansion of it has higher harmonic content. Consequently, the harmonic distortion will yield a reduction in delta sigma controller resolution (SNDR) \([8]\).

If the comb drive electrodes are used for controlling, \( k_{fb} \) will become

\[
k_{fb} = \frac{\varepsilon_0 A_{fb} V_{fb}^2}{2d_0 L_0}
\]

where, \( L_0 \) is the overlap length of the capacitor plates. It is obvious that controlling force is linear and independent of the proof mass deflection \( x \).

In the case of multiplexed controlling and sensing electrodes, same electrodes are used for both of sense and control modes and because of using variable gap electrodes for sensing to get high sensitivity, voltage to electrostatic force conversion is inherently nonlinear. Moreover, implementation of comb drive actuation structures for these modes leads to reduced sensitivity. Therefore, in this work sensing and controlling electrodes is designed separately in which comb drive electrodes apply for controlling force and variable gap electrodes are only used to sense purpose. But motion of proof mass in the drive direction varies controlling comb drive electrode gaps. To overcome this difficulty, in the proposed structure, another mass has been coupled to the first mass by a suspension system. Secondary mass is constrained in the drive direction with respect to the

![Fig 2. Proposed gyroscope model with 2-DOF sense mode and 1-DOF drive mode oscillator](image-url)
primary mass and controlling comb drive electrodes can be attached to it.

Fig. 2 shows the proposed gyroscope model consisting of two masses and a drive frame. Drive frame is implemented to mechanically decouple the drive and sense direction oscillations of $m_1$. This leads to minimize quadrature error and undesired electrostatic forces in the sense mode due to drive mode actuator imperfections [7].

Operational principle of proposed MEMS gyroscope is as follows: an external sinusoidal force at the drive mode resonant frequency is applied to the drive frame through drive electrodes. Vibrations of the frame transfer to $m_1$ through primary mass suspensions. $m_1$ is free to oscillate in both of the sense and drive directions, but $m_2$ is constrained in the drive direction by secondary mass suspensions. Therefore, in the presence of an angular rate input, a sinusoidal Coriolis force at the frequency of drive mode oscillation induced only on the primary mass and causes to vibrate in the sense direction. Coupling suspensions transfer these oscillations to secondary mass ($m_2$). Finally, the applied angular rate is detected through sensing parallel plates embedded inside the secondary mass.

As discussed above, if the amplitude of angular rate increases over the specific range, the gyroscope behaves nonlinearly. Consequently, embedding gyroscope in a closed loop controller can be advantageous to improve performance. In this case, according to Fig. (1), measured displacement is turned into mechanical force and applied to gyroscope in the opposite direction of Coriolis force, by means of controlling combs. This leads to reduction of the sense direction vibrations and gyroscope remains in the linear region.

Proposed gyroscope provides robustness fabrication in addition to linearization electrostatic controlling force. New design consists of a 2-DOF sense mode oscillator and a 1-DOF drive mode oscillator. 2-DOF dynamical systems are known to have two resonance peaks which are called in-phase and anti-phase frequencies and a flat region between of them in the amplitude of the frequency response. Operating in the flat region provides structural robustness to fabrication tolerances and environmental variations. The 2-DOF structure is based on the application of dynamic amplification effect to achieve high mechanical sensitivity without resonance. A dynamic amplification can be implemented from matching the natural frequencies of the individual 1-DOF mechanical oscillators[7, 9].

### 3. Design procedure

FEM modal simulation is used for designing of the proposed gyroscope. At first, the individual 1-DOF sense mode oscillators are designed and simulated to achieve identical natural frequencies ($\omega_1 = \omega_2$). In the next step, these oscillators are attached by coupling suspension system. Coupling suspension dimensions are determined based on needed bandwidth. Finally, 1-DOF drive mode oscillator is designed by adding a drive frame. To achieve maximum dynamic amplification, drive and sense mode natural frequencies must fulfil the following condition: $\omega_d = \omega_1 = \omega_2$. Proposed gyroscope is designed to achieve operating frequency and bandwidth of 20 kHz and 600 Hz, respectively. Table I shows the summary of the proposed design parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Analytical values</th>
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<tr>
<td>Primary mass (Pg)</td>
<td>574.2</td>
</tr>
<tr>
<td>Secondary mass (Pg)</td>
<td>574.2</td>
</tr>
<tr>
<td>Primary and secondary mass suspensions (N/m)</td>
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</tr>
<tr>
<td>Coupling suspension (N/m)</td>
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</tr>
<tr>
<td>Damping ($\mu$N.s/m)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### 4. Simulation results

Finite element simulation was carried out to verify the operation of the proposed gyroscope. Fig. 3a and 3b shows in-phase and anti-phase mode of the masses in the sense direction, respectively.

Fig. 3. Modal simulation results of proposed gyroscope in the sense direction
Fig. 4 displays modal analysis in the drive direction confirming that secondary mass is constrained in this direction and only primary mass vibrated. Primary mass sense and drive mode frequency response amplitudes are displayed in Fig. 5, showing that two resonance frequencies for the 2-DOF sense mode oscillator are located at 19.7 and 20.3 kHz. The drive mode resonance frequency is located inside the sense mode flat region.

To estimate sensitivity of the proposed gyroscope, transient analysis was carried out. There are two time varying input sources in the device: the sinusoidal voltage applied to the comb drives to keep the mass oscillating in the drive direction, and the step source which is used as the angular velocity of the sensor and its substrate about the z-axis. With an angular rotation of 50 °/s around z-axis at 1 millisecond and primary mass oscillation amplitude of 120 nm in the drive direction, the produced displacement in the sense direction due to Coriolis force in secondary mass is 32 nm as shown in Fig. 6.

7. Conclusion

A new design of microgyroscope with control capability was presented. In this design, control force applied by comb drive electrodes, to make conversion of voltage to electrostatic force linear. This linearity improves closed loop control system resolution. The structure was formed as a 2-DOF sense mode oscillator and a 1-DOF drive mode oscillator. To analyse the device performance under the application of angular velocity, a rate table characterization is also carried out. This resulted in secondary mass displacement of 32 nm corresponding to the induced Coriolis force with angular rotation of 50 °/s.

Fig 4. Modal simulation results of the proposed gyroscope in the drive direction

Fig 5. Primary mass sense and drive mode frequency response amplitudes

Fig 6. Step response of secondary mass sense mode in time domain

References


