Design and Simulation of a New Decoupled Micromachined Gyroscope

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Abstract. This paper reports on a new decoupled micromachined gyroscope. The proposed sensor is a dual mass type, electrostatically driven to primary mode oscillation and senses, capacitively, the output signal. Full decoupling between drive and sense modes minimizes the mechanical crosstalk. Three different designs are introduced in this work. Drive and sense amplitudes, mechanical and electrical sensitivities, quality factors and approximate bandwidths are extracted analytically and the results are confirmed using finite element analysis. The first design shows drive and sense modes resonance frequencies of 4077 Hz and 4081 Hz respectively; with a frequency mismatch lower than 0.1%. The drive and sense capacitance are 0.213 pF and 0.142 pF respectively. The mechanical and electrical sensitivities are 0.011 μm/(°/s) and 2.75 mV/(°/s) respectively. The third design shows significantly improved mechanical and electrical sensitivities of 0.027 μm/(°/s) and 6.85 mV/(°/s) respectively.

Keywords: MEMS, Micromachined Gyroscope, Finite element analysis,

1. Introduction

MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology [1, 2]. The Gyroscope is an interesting MEMS device which is used as an essential component in any navigation system. It has a wide variety of applications ranging from satellite attitude sensing to rollover detection in automobiles [3]. The Gyroscope’s family is a large one, and it has many types such as mechanical, optical, and vibratory. During the last decade, MEMS gyroscopes have attracted lots of attention due to their small size, batch fabrication, Integrated Circuit (IC) compatibility, low cost, and acceptable moderate performance for most applications. Representative examples of previous MEMS gyroscope designs are given in [4-8].

This work introduces a new design for a dual mass gyroscope with decoupled drive and sense modes. The proposed structures are designed according to DRIE CMOS-MEMS process [9] and simulated using ANSYS software. The nonlinearity of the sense combs [5] is avoided by using lateral combs, which has the advantages of linear operation, large capacitance, and large dynamic range. The designed sensor needs only two lithography steps, and hence, reduces the manufacturing complexity. Furthermore, the all silicon material used lowers the temperature sensitivity problem. In addition, this structure can be implemented using silicon on insulator (SOI) wafers which lowers the parasitic capacitance. The simulated results show good mechanical and electrical sensitivities, as well as, a good resolution, that is limited by the readout electronics. Performance can be significantly enhanced if the sensor is manufactured with a high aspect ratio technology.
2. Gyroscope Design

2.1. Structure

All vibratory MEMS gyroscopes are based on transferring energy between two modes of oscillation. Applying an appropriate AC voltage across the drive comb-finger produces an electrostatic force. This force is a function of the number of comb fingers, structure thickness, applied potential difference and gap separation between fingers [10]. If the drive force is at the resonance frequency of the drive mode, the drive mode displacement is amplified by the mechanical quality factor of the drive mode. When exposed to external rotation rate around the $z$-axis, an induced Coriolis force is produced along the $y$-axis. This force is a function of the drive mode velocity, the external rotation rate, and the mass. So, maximizing the drive mode amplitude and the structure mass are required to sense small input rotation rates. The Coriolis force excites the sense mode oscillation (secondary mode along the $y$-axis). If the sense mode is at the same resonance frequency of the drive mode (matched mode operation) the sense displacement amplitude is amplified by the mechanical quality factor of the sense mode.

Fig. 1 shows a schematic diagram of the first proposed gyroscope which will be referred to as “new decupled micromachined gyroscope (NDMG)”. It consists of an outer frame, an inner mass, and a sense element. The outer frame has a mass $m_d$ and is anchored to the substrate by the first beam suspension, (beam 1). It carries two comb assemblies; the first comb is used as a drive actuator, whereas the second is used to sense the drive mode displacement for feedback control purposes. The inner mass ($m_i$) is attached to the outer frame via suspension beam 2 and to the sense element by suspension beam 3, as shown schematically in Fig. 1. The inner mass decouples the drive mode from the sense mode by using two different beams support, beam 2 and beam 3. The sense element supports
the sense combs. It is anchored to the substrate through suspension beam 4, and to the inner mass via a simple beam (beam3), and has a mass $m_s$. The mechanical crosstalk is minimized due to the decoupling between the drive and sense masses.

The main limitation of this design is its low capacitance which results in low sensitivity. This problem can be alleviated by introducing a large number of sense mode combs as shown in Fig. 2. This configuration will be referred to as “modified decoupled micromachined gyroscope (MDMG)”. Finally, the third gyroscope design, named, “High Performance Decoupled Micromachined Gyroscope (HPDMG)”, aims at increasing both the drive amplitude and the sense capacitance by increasing the drive force and the number of comb drive fingers as demonstrated in Fig. 3.

2.2. Design

The actual determination of the physical parameters of the above designs is not simple. The design starts by adjusting the drive mode to achieve visible oscillations. During this process, the internal and external elements must be sized simultaneously to keep the resonance frequencies of the two modes matched.

The crab-leg suspension used in this design (cf. Fig.4 (a)) has a spring constant that is more compliant along the $x$ axis and very stiff along the $y$ axis. The stiffness along the $x$ and $y$ direction is expressed as [11]:

$$K_x = \frac{E \cdot h \cdot w_3^3 \cdot (l_a + 4 \cdot l_b)}{l_b^3 \cdot (l_a + l_b)}, \quad K_y = \frac{E \cdot h \cdot w_3^3 \cdot (l_b + 4 \cdot l_a)}{l_a^3 \cdot (l_a + l_b)}$$

(1)

Where $E$ is the Young's Modulus, and $h$ is the height of the structure.

A part of a comb-drive assembly is shown schematically in Fig. 4 (b). It is actuated electrostatically with a produced force that can be expressed as [10]:

$$F_d = \frac{1}{2} \frac{N \cdot e_a \cdot h \cdot V^2}{g_o},$$

(2)
Where $N$ is the number of fingers, $\varepsilon_0$ is the free space permittivity, and $V$ is the voltage difference across the comb structure.

If the drive force matches the resonance frequency of the drive mode, the corresponding displacement is:

$$X_d = \frac{Q_x \cdot \frac{F_d}{K_x}}{Q_x},$$

(3)

Where $Q_x$ is the mechanical quality factor of the drive mode vibrations.

Referring to Fig. 4(b), the capacitance of the comb-drive can be computed using parallel plate approximation as:

$$C = \frac{2.\pi \cdot \varepsilon_0 \cdot h \cdot (l_o - x)}{g_o}$$

(4)

Finally, the resonance frequencies of the sense mode $\omega_y$ and drive modes $\omega_x$ can be expressed, respectively, as:

$$\omega_y = \sqrt{\frac{K_{sens}}{m_{sens}}}, \text{ and } \omega_x = \sqrt{\frac{K_{drive}}{m_{drive}}}$$

(5)

Equating the two resonance frequencies for matched mode operation, we get a formula for the sense mass as a fraction of the drive mass. If the sensor is exposed to a constant rotation rate, $\Omega$, along the $z$-axis, Coriolis force, $F_c$, is induced along the $y$-axis, and can be expressed as:

$$F_c = -2.\pi \cdot \Omega \times \dot{X} = -\frac{2.\pi \cdot \Omega \cdot \omega_x \cdot Q_x \cdot \frac{F_d}{K_x}}{K_y} \sin(\omega_x t)$$

(6)

For matched mode operation, this force results in a sense mode displacement at resonance of:

$$y = \frac{Q_y \cdot \frac{F_c}{K_y}}{K_y}$$

(7)

Where $Q_y$ is the mechanical quality factor of the sense mode vibrations.

The mechanical sensitivity and the output signal of the sensor are defined as:

$$S_m = \frac{y}{\Omega} = \frac{2.\pi \cdot \omega_x \cdot Q_x \cdot \frac{F_d}{K_x}}{K_y}, \quad V_o = \frac{C_2}{C_1 + C_2} \frac{V_m}{2} + \frac{y \cdot V_m}{2 J_o}$$

(8)

The sense combs are designed to have an overlapping length, $l_o$, of 20 $\mu$m. Using equation (8), the rate of change of the output voltage per unit change in $y$ equals 0.25 V/$\mu$m for carrier signal amplitude of 10 V.

3. Results and Discussion

3.1. Analytical Results

Table 1 summarizes the analytical results. NDMG has simple structure, but its electrical sensitivity is low due to the small driving electrostatic force, and the sense capacitance is also low. Although MDMG has a larger sense capacitance and smaller area than the others, it suffers from very low
electrical sensitivity, and small mass. HPDMG solved the problem of these two versions through efficient utilization of the available device space.

Table 1 design analytical parameter for the proposed structures

|            | NDMG | MDMG | HPDMG |
|------------|------|------|-------|
| Area (mm²) | 1.4352 | 1.3 | 1.453 |
| Suspension | X-direction | 15.48 | 15.48 | 13.31 |
| Drive Force | pN | 0.797 | 0.707 | 1.161 |
| Drive-mass | N | 20.501 | 14.6794 | 16.7648 |
| MASS (µg) | Sense-mass | 30.9498 | 22.3220 | 26.6474 |
| Capacitance | drive mode | 0.213 | 0.213 | 0.32 |
| Drive Force | (µN) | 3.235 | 2.57 | 5.171 |
| Drive-mass | N | 22.8202 | 16.4660 | 19.5052 |
| Sense-mass | 15.48 | 15.48 | 13.31 |
| Mechanical sens. | µm/(º/s) | 0.011 | 0.008 | 0.019 |
| Dynamic range | (º/s) | ± 380 | ± 330 | ± 250 |

Table 2 ANSYS modal and harmonic analysis results

|            | NDMG | HPDMG |
|------------|------|-------|
| Area (mm²) | 1.421 | 1.416 |
| Drive freq. | (Hz) | 4077 | 3778 |
| Sense freq. | (Hz) | 4081 | 3774 |
| x₀ (µm) | 3.144 | 5.588 |
| y₀ (µm) | 20.501 | 22.3220 | 26.6474 |
| Mechanical sens. | µm/(º/s) | 0.011 | 0.008 | 0.019 |
| Electrical sens. | µm/(º/s) | 0.011 | 0.008 | 0.019 |
| Total mass | µg | 28.806 | 29.203 |
| Dynamic range | (º/s) | ± 250 | ± 180 |
| Bandwidth | (Hz) | ~ 66 | ~ 61 |
| Quality factor, Qₓ | ~ 53 | ~ 54 |
| Total Quality factor | ~ 62 | ~ 63 |

3.2. Finite Element Analysis using ANSYS

Table 2 summarizes the main numerical results presented in this paper. The high performance decoupled micro gyroscope (HPDMG) has better performance than that of the new decoupled micro gyroscope (NDMG). The performance enhancement is due to the efficient use of the silicon area to increase the drive force and the sense capacitance. The area of HPDMG is 0.35% smaller than that of the NDMG. On the other hand, the dynamic range of the HPDMG is narrower than that of NDMG, but this can be eliminated by increasing the length of sense mode comb fingers.

Figures 5 through 8 show the modal analysis for the NDMG, and HPDMG as obtained using finite element analysis (ANSYS). Fig. 5 shows the drive mode shape for NDMG with a natural frequency of 4077Hz. The translational mode shape displacement is in good agreement with the analytical calculations. Fig.6 shows that the secondary mode has also a translational mode shape at a resonance frequency of 4081Hz. The frequency mismatch is only 0.09%. Figures 7, 8 show the same analysis for the HPDMG.
Fig. 9 shows the frequency response of both the drive and sense modes displacements. This curve shows a maximum $x$- and $y$-displacements of $3.144 \, \mu m$ and $11 \, nm$, respectively, at resonance. These values are computed for an input rotation rate of $1 \, ^\circ/s$. The drive mode Q-factor is about 54, and that of the total effective Q for both the sense and drive vibrators is around 63. The mechanical sensitivity is $0.011 \, \mu m/\, ^\circ/s$. The electrical sensitivity is $2.75 \, mV/\, ^\circ/s$. It is interesting to note that the simulation results are in reasonable agreement with the analytical calculation. Finally, figure 10 shows the harmonic analysis for the third version (HPDMG) as obtained using ANSYS. The maximum drive mode displacement is $5.655 \, \mu m$, and the maximum sense mode displacement is $0.0273 \, \mu m$. The drive mode Q-factor is about 54, and that of the total effective Q for both the sense and drive vibrators is about 63. The mechanical and electrical sensitivities are $0.027 \, \mu m/\, ^\circ/s$ and $6.75 \, mV/\, ^\circ/s$ respectively.

4. Conclusions
This paper introduced a new structure for decoupled vibratory MEMS gyroscope. It is a dual mass type, electrostatically driven to resonance and capacitively senses the output. The all silicon sensor minimize the temperature sensitivity problems. Fabricating the sensor through DRIE CMOS-MEMS process enables monolithic integration with the read-out electronics, which minimize the parasitic capacitance. Mechanical cross talk is reduced significantly by decoupling both modes of oscillations. Significant performance enhancement is expected if a high aspect ratio technology is used.

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