A Novel of MEMS Resonant Gyroscope Using DETF as Sensing Structure

Uvi Desi Fatmawati¹,a, Fan Shang Chun¹,b, Zhanshe Guo¹,c
¹School of Instrument science and Opto-Electronics engineering, Beihang University
Beijing, P.R. China
afatmawati_muslimah@yahoo.co.id, bfsc@buaa.edu.cn, cguozhanshe@buaa.edu.cn

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Abstract. Nowadays MEMS product is widely used in all fields such as industry, automation, aerospace, marine, etc. With advances fabrication and lowering cost, MEMS product is very useful and its simple design enabling the user use it easily. This research introduced a new design of MEMS resonant gyroscope using DETF as sensing structure. The decoupled DETF has been designed to be able to produce the natural frequency of 80 KHz, while the whole gyroscope structures generate natural frequency of 3511.8 Hz. Above condition is done to avoid force miss detection in sense mode and drive mode, which has become the biggest problem in gyroscope design. The result showed that the new design of MEMS Resonant Gyroscope is feasible.

1. INTRODUCTION

MEMS gyroscope is one type of MEMS inertia devices to measure the angular rate along the fixed axis. Roughly, based on principle detection there are two types of MEMS gyroscope: 1. Vibratory MEMS gyroscope. 2. Optical MEMS gyroscope [1]. In fact, one type of MEMS vibratory gyroscope - called - MEMS Resonant Gyroscope gives better performance than the others.

Based on [2] MEMS Resonant Gyroscope has become one of the most important research areas because of its advantages of little bulk, low power consumption and light weight, high precision and well stability. In 2002, University of California-Berkeley [3] fabricated MEMS Resonant Gyroscope using DETF which can reached sensitivity of 0.042 Hz/deg/sec. Another research has been done by Zhu, et al [4] on his research, DETF design for MEMS Resonant Gyroscope which can reached sensitivity of 20 mHz/deg/sec has been proposed. The most important in MEMS Resonant Gyroscope is the design of DETF as the sensing structure. It will determine the response of the gyroscope. A novel of MEMS Resonant Gyroscope in this research was built as decoupled on each structure but the detail elaboration in this paper is the DETF as sensing structure. Consequently, compared with those research [3,4], our research can make better sensitivity.

Gyroscope using Coriolis Effect then it is detected by using vibratory sensing element has some major problem. The Coriolis force on sense mode as the result of angular velocity applied on gyroscope is very small comparing to the noise force on drive mode. We can see the difference by comparing the displacement at sense mode and drive mode. This condition makes gyroscope will do miss-detection. The vibratory sensing element that should detect only the Coriolis force is interfered by another force. If so, the sensing output is not relevant anymore. To solve this problem we can distinctively set-up the higher natural frequency in DETF as sensing structure and set-up the lower natural frequency of whole gyroscope structures. Dimension parameters are used to set-up the structure’s natural frequency.
Therefore this research is absolutely dimensionless. Using this method, the result showed that our design can reached the sensitivity of 0.609 Hz/deg/sec.

Consecutively, some parameters used in this research are analyzed by MATLAB, the mechanical model simulations and analyses are carried out by ANSYS. For verify the simulation result, the formula related to this research was described.

2. METHOD
a. Structures and Principles
A schematic of MEMS Resonant Gyroscope is shown in figure 1. The working principle can be described as: The proof mass is driven using embedded lateral comb drive actuators. If an external rotation is applied to the chip at the Z-axis direction, the Coriolis force will be acting on the proof mass. Then it is transferred to the DETF through U-beam suspensions and to the lever mechanism. The transferred Coriolis force called axial force. Moreover, the amplified force is communicated axially onto two DETF resonators. The decoupled DETF has been designed to be able to produce the natural frequency of 80 KHZ, while the whole gyroscope structures generate the natural frequency of 3511.8 Hz. When there is axial force induces in one end of DETF, the DETF natural frequency will change to the resonant frequency. The difference between natural frequency and resonant frequency is called by the implied force.

Figure 1. Design of decoupled MEMS resonant gyroscope

a. Structures optimization and Analysis
Theory analysis: In this research, the theory analysis is divided into 2 parts; theory for whole gyroscope structures and theory for DETF as sensing structures.

Whole Gyroscope: In MEMS resonant gyroscope with the proof mass as driven direction, the changed capacitance in driving proof mass can be given by:

\[
\frac{dc}{dt} = N_p \varepsilon_0 \varepsilon_r \frac{h}{g_p}
\]

(1)

Where \(N_p\) is the number of proof mass driving comb, \(\varepsilon_0\) and \(\varepsilon_r\) are vaccum dielectric constant and relative dielectric constant, \(h\) is thickness of proof mass, \(g_p\) is proof mass comb drive gap. From formula (1) the electrostatic force and the proof mass displacement can be obtained by:

\[
F_{ec} = \frac{1}{2} \cdot \frac{dc}{dt} \cdot V^2
\]

(2)

\[
y_0 = Q \cdot \frac{F_{ec}}{k}
\]

(3)

Where \(V\) is driving voltage, \(Q\) is quality factor, \(k\) is U-beam suspension stiffness. Describing mass of proof mass (\(m\),
rotational velocity in proof mass ($\Omega$) and sinusoidal wave in centre of proof mass ($W_0$), the Coriolis force which induced in proof mass is given by:

$$F_c = 2m \Omega W_0 y_0$$

(4)

Consequently, the Coriolis force in centre of proof mass will produce axial force that encourages DETF. Thus, the formula of axial force is given by:

$$F = F_c X$$

(5)

Where $X$ is the amplify lever mechanism in structures.

**DETF sensing structure**: A DETF resonator is the simplest form of strain-sensitive dynamically balanced structure. When the axial force is applied on one end of DETF, the resonant frequency of the DETF sensitive element will change because of the change of inner stress. The principal of changed beam frequency depend on changed beam stiffness. The undamped mathematical equation of the DETF beam is given by:

$$EI \frac{d^4 \omega(x,t)}{dx^4} - Y \frac{d^2 \omega(x,t)}{dx^2} = -\rho S \frac{d^2 \omega(x,t)}{dt^2}$$

(6)

Where $\omega(x,t)$ is beam dynamic deflection, $I$ is beam moment of inertia, $S$ is cross sectional area, $E$ is material elasticity modula and $\rho$ is material density. When $I = \frac{W_i H_i^3}{12}$ and $S = W_i H_i$, mostly $W_i / H_i > 5$.

Assuming that the beam is according to the basic modal vibration, then the solution of mathematical equation (6) will be well-understood as:

$$\omega(x,t) = W(x)e^{i\omega_1 t}$$

(7)

Where $W(x)e$ is vibration mode function. The equation (6) substitute into (7) then we can get differential equation as follow:

$$\frac{d^4 W}{dx^4} - \frac{E}{EI} \frac{d^2 W}{dx^2} - \frac{\rho S}{EI} \omega_1^2 W = 0$$

(8)

For DETF with driving mass, formula of natural frequency and resonant frequency are explained as follow [5]:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{198.457 E I}{(0.3965 M_i + m_i) L_i^2}}$$

(9)

$$f = f_0 \sqrt{1 + \frac{0.02458 L_i^2 F}{EI}}$$

(10)

Where $E$ is elastic modula of the silicon material, $\rho$ is density of silicon material, $L_i$ is length of DETF beam, $H_i$ is thickness of DETF beam, $W_i$ is width of DETF beam, $I$ is Moment of Inertia, $M_i$ is mass of DETF single beam, $m_i$ is mass of DETF comb drive. From equation (9) and (10) by changed the DETF natural frequency with whole gyroscope structures natural frequency (after analyze using ANSYS modal analysis), the sensitivity of whole gyroscope structures can be described by

$$Sens = \frac{f-f_0}{\Omega}$$

(11)

**3. RESULT**

MEMS Resonant Gyroscope structures in this research is decoupled. Firstly, In order to get a larger Coriolis force, DETF was designed for generates the natural frequency of 80 KHz. Using ANSYS modal analysis, the DETF natural frequency has been analyzed as shown in table 1 and the mode shapes are shown in figure 2. Compare to another mode shape, the first mode shape gives the lowest frequency.
Table 1. DETF natural frequency in each mode shape

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>1st (Hz)</th>
<th>2nd (Hz)</th>
<th>3rd (Hz)</th>
<th>4th (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DETF</td>
<td>88611</td>
<td>91465</td>
<td>94823</td>
<td>97754</td>
</tr>
</tbody>
</table>

Another analysis has been used for determine the DETF working mode. Figure 3 showed the harmonic analysis of DETF resonant. Harmonic analysis gives the ability to predict sustained behavior of structures. Based on that figure, the DETF resonant structure design can successfully overcome the resonant, especially in the first mode shape. It gives the biggest resonant compare with another mode shape. From those analyses, the result showed that first mode shape give the lowest frequency but its lowest frequency can gives the bigest resonant. So we conclude that DETF 1st mode shapes can be the working mode.

Figure 3. Harmonic analysis of DETF resonant

Secondly, leverage mechanisms are used to amplify the Coriolis force. Based on the formulas mentioned above, some parameters in whole gyroscope structures as shown in table 2 has been designed in ANSYS. Meanwhile, before we design in ANSYS, these parameters should be simulate in MATLAB using the explained formulas to ensure that the design results are correct.

Table 2. Design parameters of MEMS resonant gyroscope whole structures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DETF beam length</td>
<td>$L_i$</td>
<td>700 E-6 m</td>
</tr>
<tr>
<td>DETF beam thickness</td>
<td>$H_i$</td>
<td>65E-6 m</td>
</tr>
<tr>
<td>DETF beam width</td>
<td>$W_i$</td>
<td>14E-6 m</td>
</tr>
<tr>
<td>Mass of DETF comb</td>
<td>$m_i$</td>
<td>5E-9 kg</td>
</tr>
<tr>
<td>Number of DETF comb</td>
<td>$N_i$</td>
<td>56</td>
</tr>
<tr>
<td>DETF comb finger gap</td>
<td>$g_i$</td>
<td>2E-6 m</td>
</tr>
<tr>
<td>Length of proof mass</td>
<td>$L_p$</td>
<td>1390E-6 m</td>
</tr>
<tr>
<td>Thickness of proof mass</td>
<td>$h$</td>
<td>65 E-6 m</td>
</tr>
<tr>
<td>Width of proof mass</td>
<td>$W_p$</td>
<td>1473,16E-6 m</td>
</tr>
<tr>
<td>Mass of proof mass</td>
<td>$m$</td>
<td>310,123 E-7 kg</td>
</tr>
<tr>
<td>Number of proof mass comb drive</td>
<td>$N_p$</td>
<td>46</td>
</tr>
<tr>
<td>Proof mass comb drive gap</td>
<td>$g_p$</td>
<td>5E-6 m</td>
</tr>
<tr>
<td>Driving voltage</td>
<td>$V$</td>
<td>20 V</td>
</tr>
</tbody>
</table>

Generally, the amplified lever mechanism ($X$) in this design is 5.33 and the U-beam suspension stiffness ($k$) is 42,1204. In order to determine the vibration characteristics (natural frequencies and mode shapes) and working mode of whole gyroscope structure, ANSYS modal analysis has been used to analyze. The natural frequency for a whole gyroscope structures as shown in table 3 and the mode shapes are shown in figure 4.

Table 3. MEMS resonant gyroscope mode shapes natural frequency

<table>
<thead>
<tr>
<th>MEMS gyroscope natural frequency mode shape (Hz)</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS</td>
<td>3511.8</td>
<td>12296</td>
<td>14036</td>
<td>70707</td>
</tr>
</tbody>
</table>
Based on table 3 the first mode shape is chosen for whole gyroscope structure’s working mode because the difference frequencies between the first mode shape and another mode shape are quite far. It shown that the gyroscope structure can works stably while another mode is only interference mode.

To see the displacement ratio between proof mass and DETF, ANSYS static analysis is used. The result showed in figure 5. when 1000 μN force applied in centre of proof mass, the displacement of proof mass is 6.4348 μm while the displacement of DETF is 0.87187x10⁻² μm. Therefore, the displacement ratio in this model is 1.3549x10⁻³.

In the field of sensor research, sensitivity analysis is needed to determine sensitivity level of the sensor. Sensitivity analysis will given by theoretical side based on the described formulas. By the natural frequency analysis we can get the value of Coriolis force, axial force and differential frequency output in every implied rotational velocity as shown in table 4.

Table 4. Value of Coriolis force, axial force and differential frequency output in every implied rotational velocity.

<table>
<thead>
<tr>
<th>Ω (deg/sec)</th>
<th>Fc (N)</th>
<th>F (N)</th>
<th>Δf (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.7526x10⁻⁴</td>
<td>7.3357x10⁻⁴</td>
<td>6.1707</td>
</tr>
<tr>
<td>50</td>
<td>0.0014</td>
<td>0.0037</td>
<td>30.7459</td>
</tr>
<tr>
<td>100</td>
<td>0.0028</td>
<td>0.0073</td>
<td>61.2272</td>
</tr>
<tr>
<td>150</td>
<td>0.0041</td>
<td>0.0110</td>
<td>91.4507</td>
</tr>
<tr>
<td>200</td>
<td>0.0055</td>
<td>0.0147</td>
<td>121.4227</td>
</tr>
<tr>
<td>250</td>
<td>0.0069</td>
<td>0.0183</td>
<td>151.1496</td>
</tr>
<tr>
<td>300</td>
<td>0.0083</td>
<td>0.0220</td>
<td>180.6371</td>
</tr>
</tbody>
</table>

In the field of sensor research, sensitivity analysis is needed to determine sensitivity level of the sensor. Sensitivity analysis will given by theoretical side based on the described formulas. By the natural frequency analysis we can get the value of Coriolis force, axial force and differential frequency output in every implied rotational velocity as shown in table 4.

Table 4. Value of Coriolis force, axial force and differential frequency output in every implied rotational velocity.

From table 4, by using MATLAB software, relationship between Ω and Δf are shown in figure 6, while the relationship between
axial force and resonant frequency are shown in figure 7. From those figures, the gyroscope structure was designed to work in angular rate $\pm 300$ deg/sec. In range of its working angular rate, the $\Delta f$ and $F$ trend of graph is relatively linear. But in higher angular rate out of working mode, the trend of $\Delta f$ and $F$ are not linear anymore. Consequently, the sensitivity for MEMS resonant gyroscope in its working angular rate is 0.609 Hz/deg/sec.

4. CONCLUSION

In this research, the new design of MEMS resonant gyroscope was presented as clear. The MEMS resonant gyroscope was built as decoupled structure start from DETF as sensing mechanism. DETF was designed for measure 80 KHz natural frequency. For reduced the noises detection made by driving mode, the natural frequency of DETF was designed higher than natural frequency for whole gyroscope. Based on ANSYS modal analysis the natural frequency of DETF is 88611 Hz, while the natural frequency of whole gyroscope is 3511.8 Hz. Based on ANSYS static analysis and theoretical sensitivity analysis the displacement ratio and sensitivity of this design is $1.3549 \times 10^{-3}$ and 0.609 Hz/deg/sec. This design is feasible because its small ratio and high sensitivity. The small ratio means that the driven forces have little impact to the DETF in the driven direction.

5. DISCUSSION

Theory analysis and optimum design for the MEMS resonant gyroscope has been introduced in this research. The FEM simulation using commercial ANSYS software is used to simulate the design. In order to improve the research on MEMS resonant gyroscope, main future work can be expressed as :

- The design of MEMS resonant gyroscope should be fabricated in order to make a deep analytical design and improve the ability
- The mathematical model should be improved for further explanation and modify the design parameters
- Increase the number of proof mass comb drive, in order to make the more sensitiv design

6. REFERENCES