Design of A New Structure Quartz MEMS Gyroscope with High Sensitivity

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Abstract. This paper proposes a new structure of quartz MEMS gyroscope. Compared with the traditional double-ended quartz gyroscope, the grooves are symmetrically arranged in the sense tuning forks of new gyroscope, and the two pairs of extra electrodes are added on the grooves. The extra symmetrical sense electrodes can increase the strong electric field, and the increased area of sense electrodes is beneficial to detect charge signals. The ANSYS finite element software is used to simulate the designed structure. The influence of frequency difference is analyzed by modal type, and the parameters of quartz tuning fork gyroscope are optimized to find the suitable structure, the frequency difference of the gyroscope is 203.42Hz. At the same time, the sensitivity is analyzed by harmonic type. The results show that the increasing of the area electrode is efficient, the efficiency of electric field detection is enhanced. The sensitivity of the quartz MEMS gyroscope is increased by more than 15%.

1. Introduction

The quartz MEMS gyroscope is a superior miniature inertial instrument. Over the past decades, it is widely used in defense and aerospace fields, such as tank stabilizer, self-propelled artillery and satellite attitude control. America BEI company have applied the quartz MEMS gyroscope in missile autopilot [1]. Due to the rapid development of the industrial automation and information technology, the quartz MEMS gyroscope have expanded various new applications, such as internet of things, wearable devices, medical devices [2,3], the demand of quartz MEMS gyroscope is increasing rapidly. Nowadays the requirement of the quartz MEMS gyroscope performance is higher and higher.

Through many analysis of various quartz MEMS gyroscopes, we have found some difficulties, for example complex structure, high coupling error and the difficulty of the fabrication process. All of these have an effect on well performance indicators of the quartz MEMS gyroscope. In order to increase the sensitivity, more and more researches focus on the optimization of the gyroscope’s structure. Japan ISHINOMAKI university have researched single-ended tuning fork structure, by adjusting the length of the base to change the drive frequency and the sense frequency, getting the frequency difference. They can calculate sensitivity and response characteristics of gyroscope by analyzing two maximum displacements in horizontal and vertical direction, but the coupling error of single-ended tuning fork is large, it causes the application of limitations [4]. In the paper [5], they have analyzed the double-ended tuning fork gyroscope structure, which is simulated by finite element method, by changing the beam structure of tuning forks’ root and sense tuning forks’ electrode, through lithography and wet etching to produce, these ways have been verified that the design of
double-ended tuning fork quartz resonator is a flat supporting gyroscope sensor. However, it has a low sensitivity, which is difficult to improve. Seiko Epson Corp in 2011 have published patent, according to the classic "U" type quartz gyroscope, a "H" shaped section vibration arm beam structure is designed, through fabricating the grooves on the surface vibration of beams, the structure has improved the incentive efficiency of internal vibration beam excitation electric field intensity and electrode, but the designed structure has some chamfer on the grooves, that is very difficult to process [6]. Beijing Institute of Technology has been engaged in the research of quartz tuning fork gyroscope. It has researched and produced a double-ended tuning fork gyro sensor. Its sensitivity is 18.134 mV/°/s. The gyro sensor has a larger volume, which can have a well accuracy by optimizing [7].

In this paper, a new design of a quartz tuning fork gyroscope MEMS structure is proposed. Based on the traditional structure, the designed structure has grooves through proper parameter, grooves are arranged two pairs of electrodes. The sense tuning forks can produce high efficiency to detect in the electric field, a high sensitivity gyroscope can be obtained.

2. Structure Design

2.1. Structure of quartz MEMS tuning fork gyroscope

Many kinds of quartz MEMS tuning fork gyroscopes have been developed by BEI company. The typical "STD4" gyroscope has the advantages of simple structure and mature production technology, and the coupling error is low [8]. Based on "STD4" tuning fork gyroscope, we have designed the structure of gyro sensor, as is shows in Figure 1. The structure is axis-symmetric in x-axis, which comprises of drive tuning forks, sense tuning forks, support frame, the drive electrodes and the sense electrodes. A pair of symmetrical grooves are arranged on the sense tuning forks. In this way the thickness of the sense tuning forks is decreased, and the displacement of the sense tuning forks can be amplified under effect of the same Coriolis force.

![Figure 1. Structure of the gyroscope.](image)

Figure 2 shows the cross section of sense tuning fork with grooves. $H$ is the thickness of the sense tuning fork, and $W$ is the width of the sense tuning fork. The depth of grooves is $b$, and the width of grooves is $W-2a$. Different parameters of grooves cause different sensitivity, and the optimal parameters can be selected through analyzing.
2.2. Design Concept

The quartz crystal is a piezoelectric material. According to the positive and negative piezoelectric effects, under the action of the stress tensor $T$ and the electric field $E$, the quartz crystal can produce the piezoelectric strain $S_{electric}$ and the piezoelectric potential shift $D_{electric}$, the relations can be expressed as\[9]\]

$$
\begin{align*}
S_{electric} &= d_1 \cdot E \\
D_{electric} &= d \cdot T
\end{align*}
$$

(1)

The piezoelectric constant $d$ is a matrix, the $d_i$ is the transposed matrix of $d$.

$$
\begin{align*}
d &= \begin{pmatrix}
d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\
0 & 0 & 0 & 0 & d_{14} & -2d_{11} \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\end{align*}
$$

(2)

$T$ can be detected conveniently with more areas of the sense electrodes, this method can improve the performance of the gyroscope. In order to increase the areas of electrodes, we have arranged the two extra pairs of electrodes on the grooves. The $x$ axis of the tuning fork gyroscope is the reference axis, the angular velocity input axis is $y$ axis, so there is an Coriolis force $F$. The output axis is the $z$ axis. In the designed structure with the grooves, one sense tuning fork consists of three parts, their inertia moments are $I_1$, $I_2$ and $I_3$. In order to simplify the analysis, the relationship of each inertial moment can be expressed as

$$
I_{all} = I_1 + I_2 + I_3
$$

(3)

$$
I_1 = I_3 = \frac{aH^3}{12}
$$

(4)

$$
I_2 = \frac{(W-2a)(H-2b)^3}{12}
$$

(5)
Figure 3. Parameter of grooves’ structure and inertia moment.

According to the expressions (3), (4) and (5), the inertial moment of the sense tuning fork $I_{all}$ is determined by the parameters $a$ and $b$. As shown in Figure 3, when $a$ is the minimum and $b$ is the maximum, $I_{all}$ is the minimum.

When a voltage signal applied on the drive electrodes, and the drive tuning forks can vibrate. The sense tuning fork is bending in the direction of the $z$ axis, as followed in Figure 4.

Figure 4. Deformation of the sense tuning fork.

The displacement of sense tuning fork $M_{max}$ can be expressed as [10]

$$ M_{max} = \frac{FLM'}{3EI} $$

(6)

Where $E'$ is Young's modulus of quartz, $L$ is the length of the sense tuning fork. Coriolis force $F$ generates shear stress, and the bending produces direct stress, but shear stress is smaller than direct stress. So the analysis has ignored shear stress of the sense tuning forks.

The direct stress of the sense tuning fork caused by the displacement can be obtained as [11]

$$ T_{max} = \frac{C_{11}HM_{max}}{L^2} $$

(7)

$C_{11}$ is the stiffness constant, and the value is $86.05e^9$ N/m$^2$.

The bending of the sense tuning forks can generate charge, which can be gathered by the sense electrodes [12]. Figure 5 is the distribution of the drive electrodes and the sense electrodes of the quartz MEMS tuning fork gyroscope.
Figure 5. Electrode distribution diagram: (a) drive electrodes; (b) sense electrodes.

The drive electrodes of the designed gyroscope and the traditional gyroscope are the same, but the sense electrodes of designed gyroscope are distributed symmetrically in the grooves.

The charge density of the sense electrodes is \( \sigma \).

\[
\sigma = d_{11} T
\]  \hspace{1cm} (8)

Where \( d_{11} \) is the piezoelectric constant, the value of \( d_{11} \) is \( 2.31 \times 10^{-12} \) C/N.

The amount of charge on the electrodes can be obtained

\[
Q = A \cdot \sigma
\]  \hspace{1cm} (9)

Where \( A \) is the effective areas of the electrodes. We can see that the amount of charge depends on the electrodes areas and the charge density, and the value of the charge determines the sensitivity of quartz MEMS tuning fork gyroscope. Our designed structure can increase the electrodes area and the displacement of the sense tuning forks, and finally improve the sensitivity of the gyroscope.

3. Finite Element Analysis

3.1. Modal Analysis

The designed structure is complex, vibration characteristics of the gyroscope need to analyze. There are many vibration modes, we change the parameters of the quartz MEMS gyroscope to get the drive mode frequency \( f_d \) and the sense mode frequency \( f_s \). The fundamental frequency of the tuning fork’s vibration can be expressed as [13],

\[
f_0 = \frac{w_0}{2\pi} = \frac{(1.8751)^2}{2\pi \sqrt{12}} \cdot \frac{t}{L^2} \sqrt{\frac{1}{\rho s^2_{22}}}
\]  \hspace{1cm} (10)

Where \( L \) is the length of the tuning fork, \( \rho \) is the density of the quartz crystal, and \( t \) represents the width or thickness of the tuning fork.

The frequency difference can be expressed as [14],

\[
\Delta f = f_s - f_d
\]  \hspace{1cm} (11)

The drive mode frequency of the traditional structure is 11039.11Hz, and the drive mode frequency of the traditional structure is 11242.18Hz. The frequency difference is 203.07Hz. Figure 6 is a modal analysis of the designed structure. In Figure 6(a), the sixth order mode is to drive the horizontal vibration mode in the \( x-y \) plane. In Figure 6(b), the seventh order mode is to sense the vertical vibration mode in the \( z \)-axis.
Figure 6. Modal analysis by ANSYS: (a) sixth order mode; (b) seventh order mode.

When the length of sense tuning forks is the same value, \( b = (1/3) \) \( H = 0.165 \) mm, and \( a \) is changed, we have simulated some points. The results of simulation are shown in Tab.1.

| No. | Parameter (mm) | Drive Frequency \( f_d \) (Hz) | Sense Frequency \( f_s \) (Hz) | Frequency difference \( \Delta f \) (Hz) |
|-----|----------------|-------------------------------|--------------------------------|-----------------------------------|
| 1   | \( a=0.045 \)  | 11022.99                      | 10500.26                       | -522.73                          |
| 2   | \( a=0.055 \)  | 11022.98                      | 10798.34                       | -224.54                          |
| 3   | \( a=0.065 \)  | 11022.98                      | 11000.01                       | 22.97                            |
| 4   | \( a=0.075 \)  | 11022.98                      | 11124.85                       | 101.87                           |
| 5   | \( a=0.085 \)  | 11022.98                      | 11201.66                       | 178.68                           |
| 6   | \( a=0.095 \)  | 11022.98                      | 11241.63                       | 218.64                           |
| 7   | \( a=0.105 \)  | 11022.98                      | 11252.65                       | 229.67                           |

According to Equation (10), the value of \( a \) can change sense frequency by changing the thickness of the tuning fork, but the value of \( a \) can’t change drive frequency.

When the length of sense tuning forks is the same value, the value of \( a = (1/3) \) \( W = 0.075 \) mm, and the value of \( b \) is changed, we have simulated some points. The results of simulation are shown in Tab.2.

| No. | Parameter (mm) | Drive Frequency \( f_d \) (Hz) | Sense Frequency \( f_s \) (Hz) | Frequency difference \( \Delta f \) (Hz) |
|-----|----------------|-------------------------------|--------------------------------|-----------------------------------|
| 8   | \( b=0.125 \)  | 11041.37                      | 11124.90                       | 83.53                            |
| 9   | \( b=0.145 \)  | 11036.33                      | 11144.04                       | 107.71                           |
| 10  | \( b=0.165 \)  | 11022.98                      | 11124.85                       | 101.87                           |
| 11  | \( b=0.185 \)  | 11016.37                      | 11796.72                       | 780.35                           |
| 12  | \( b=0.205 \)  | 11013.09                      | 12012.29                       | 999.20                           |

It is known from Tab.1 and Tab.2, the parameters of the grooves have an effect on the frequency difference of the tuning fork. If the drive frequency is close to the sense frequency, the frequency difference \( \Delta f \) will be smaller, the bandwidth of the quartz MEMS gyroscope will be limited. The robustness is not well [15,16].
3.2. Harmonic Analysis
A whole quartz MEMS gyroscope system has a tuning fork gyroscope and a system with signal processing. The sensitivity of gyroscope and the performance of signal processing circuit are important to the whole system. The sensitivity of the sensor is the ratio of the output to the input change. The output impedance of quartz tuning fork is large, so the external circuit uses charge amplifier to detect the charge sensitivity [17,18].

The length of the tuning fork is adjusted, and the frequency difference is close. Due to the error of the simulation, $\Delta f$ are not completely same. We have analyzed the relation between the parameters and charge amount.

When the value of $b = (1/3) \, W = 0.165 \, \text{mm}$, and the value of $a$ is changed. The results of simulation are shown in Tab.3 and Figure 7.

| No. | Parameter (mm) | Drive Frequency $f_d$ (Hz) | Sense Frequency $f_s$ (Hz) | Frequency difference $\Delta f$ (Hz) | Charge (fC) |
|-----|----------------|---------------------------|---------------------------|-------------------------------------|-------------|
| 1   | $a=0.045$      | 11022.99                  | 11227.45                  | 204.46                              | 0.501113    |
| 2   | $a=0.055$      | 11022.98                  | 11224.75                  | 201.77                              | 0.329089    |
| 3   | $a=0.065$      | 11022.98                  | 11228.45                  | 205.47                              | 0.323670    |
| 4   | $a=0.075$      | 11022.98                  | 11228.20                  | 205.22                              | 0.321093    |
| 5   | $a=0.085$      | 11022.98                  | 11229.94                  | 206.96                              | 0.271477    |
| 6   | $a=0.095$      | 11022.98                  | 11241.63                  | 208.78                              | 0.229174    |
| 7   | $a=0.105$      | 11022.99                  | 11228.03                  | 205.04                              | 0.205233    |

Figure 7. The relationship a and charge.

When the value of $a = (1/3) \, W = 0.075 \, \text{mm}$, and the value of $b$ is changed. The results of simulation are shown in Tab.4 and Figure 8.

| No. | Parameter (mm) | Drive Frequency $f_d$ (Hz) | Sense Frequency $f_s$ (Hz) | Frequency difference $\Delta f$ (Hz) | Charge (fC) |
|-----|----------------|---------------------------|---------------------------|-------------------------------------|-------------|
| 8   | $b=0.125$      | 11041.37                  | 11245.04                  | 203.67                              | 0.17473     |
| 9   | $b=0.145$      | 11036.33                  | 11241.54                  | 205.21                              | 0.24355     |
| 10  | $b=0.165$      | 11022.98                  | 11228.20                  | 205.22                              | 0.32367     |
| 11  | $b=0.185$      | 11016.37                  | 11237.26                  | 203.07                              | 1.13845     |
| 12  | $b=0.205$      | 11013.09                  | 11219.00                  | 205.91                              | 1.44146     |
Combing figure 4 with figure 7 and 8, we find that the value of $a$ and $b$ have some relations with the inertia moment $I$. At the same time, they have also impact on charge amount. For the parameters, we consider that the trend of the values, the structure of $b=0.205\text{mm}$, $a=0.045\text{mm}$ is the optimal structure now, the amount of charge is much more.

Comparing with the traditional quartz MEMS gyroscope and the designed quartz MEMS gyroscope. Tab. 5 has summarized the sensitivity of the two structure.

| Parameter                      | Charge sensitivity $\left(\text{fC/}^\circ/\text{s}\right)$ | Frequency difference $\Delta f \left(\text{Hz}\right)$ |
|--------------------------------|-------------------------------------------------------------|------------------------------------------------------|
| traditional tuning fork structure | 0.13814                                                    | 203.07                                               |
| new designed structure          | 2.10055                                                    | 203.42                                               |

For the new structure of quartz MEMS gyroscope, the frequency difference between drive frequency and sense frequency is 203.42Hz, which is within a reasonable value, it can obtain the maximum charge sensitivity. New quartz MEMS gyroscope’s charge are increased by about 15%, quartz MEMS gyroscope performance index is improved.

4. Conclusions
We have designed a new quartz MEMS tuning fork gyroscope structure, presenting the concept, modeling and simulating with the frequency difference and sensitivity, the application of ANSYS simulation software is vital, including modal analysis and harmonic analysis. The working mode has an reasonable resonant frequency, far away from other interference mode vibration frequency, effectively improving the anti-interference performance of the gyroscope. The novel structure of quartz MEMS gyroscope with grooves reduces the size of the components and maintains the structural symmetry of the double-ended quartz tuning fork gyroscope, while maintaining the stability of the gyroscope. By theoretical calculation and simulation analysis, the strength of the detection electric field and the efficiency of electric field detection are strong and well, the sensitivity is increased by about 15%, which lays a theoretical foundation for further research and manufacture of high performance MEMS quartz gyroscope. It also provides a reference for the standardization design and innovation of micromachines vibration gyroscope. In the future, we can design two double H-shaped cross-section grooves in the drive tuning forks.

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Author Contributions:
For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Zhang Qingyuan; Feng Lihui; Cui Jianmin; Tang Yi and Yao Yanqings presents the thought; Zhang Qingyuan and Feng Lihui designed the structure; Zhang Qingyuan contributed the analysis tools and wrote the paper.” Authorship must be limited to those who have contributed substantially to the work reported.

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