Laser Trimming Method for Reducing Frequency Split of Cylindrical Vibrating Gyroscope

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Abstract. Frequency split is the frequency difference between the driving mode and sensing mode of a vibratory gyroscope, which significantly influences the performance of cylindrical vibratory gyroscopes. In order to reducing frequency split, a method of trimming by drilling micro-holes through laser has been introduced in this paper. Firstly, the processing method of the trimming hole is determined by the finite element simulation, and then the feasibility of the method is verified by the experiment. In the experiment, the frequency split of gyroscope is reduced from 2.090Hz to 0.119Hz.

1. Introduction

A gyroscope is a device that senses the rotation of a body. Gyroscopes are widely used in many fields, such as industrial robot, consumer electronics and aerospace navigation [1-4]. The cylindrical vibratory gyroscope (CVG), is a novel, solid state gyroscope, whose work is based on the inertia effect of elastic waves[5]. Its cylindrical shell simplifies the fabrication of the resonator [6]. Without a rotary structure, this type of gyroscope proves to be high accuracy, better impact resistance and stability [7-9]. The gyroscope studied in this paper has a constant elastic alloy as its shell material. This material is more easily manufactured than fused silica, which some are made from, yet still has acceptable accuracy [6,10].

Frequency split is an important measure to evaluate the quality of a gyroscope [11]. It affects both the sensing accuracy and stability of the gyroscope, causing potential hazards in areas with high accuracy requirements [12,13]. Ideally, the frequency of the driving mode and sensing mode of the cylindrical vibratory gyroscope are equal [12]. However, frequency split is unavoidable due to manufacturing errors and disproportionate variation in density and stress [14,15]. Therefore, it is imperative to develop an effective method to minimize the frequency split.

Several studies on frequency split trimming have been reported. For example: trimming by processing grooves on the rim of the resonant ring, and holes in the base plate [16]; trimming by processing grooves on the suspension and base plate [9] etc.

In these methods, several grooves are made on the cylindrical wall of the resonator, which reduce the stiffness of the resonator. Additionally, there are many processing steps in these methods, increasing the chance of manufacturing errors. Also less attention is paid to the correlation between frequency split trimming and such factors of geometrical dimensions, removed mass and so on. The purpose of this paper is to find a method that can reduce the frequency split while keeping the gyroscope structure as intact as possible.
This paper explores a way to trim the frequency split while simplifying the processing procedures and minimizing the mass removed from the gyroscope. It discusses the main factors that influence the trimming of frequency split. The values of frequency split in trimming processes are presented based on FEM simulation. In addition, relevant experiments have also been carried out, which validated the analysis.

2. Structure and Working Principle
The structure of a typical CVG is shown in Figure 1. The resonator is the core of gyroscope which is used to produce gyroscopic effect [8]. It is made of elastic alloy and is fixed on the base by the supporting bar. Piezoelectric electrodes can be divided into two groups of driving electrodes and sensing electrodes, which are used to excite driving mode and detect sensitive mode respectively [6].

![Figure 1. The structure of cylindrical vibratory gyroscope.](image1)

The driving mode and the sensing mode are standing wave vibration with wave number of 2, and they form 45 degree angles to each other, as show in Figure 2. The Eigen frequency difference between these two modes is defined as frequency split.

The working principle of a CVG can be briefly described as follows [17,18]: Utilize the inverse piezoelectric effect, AC voltage is input to the driving electrodes to excite the vibration of the driving mode. When the gyroscope has no angular velocity input, the vibration of the sensing mode direction should be 0. When gyroscope has angular velocity input, Coriolis effect results in vibration in sensing mode direction. Because of the piezoelectric effect, the vibration in the direction of the sensing mode is converted to the voltage output of the sensing electrodes, and the input angular velocity can be calculated by this voltage.

![Figure 2. The driving mode and sensing mode of the cylindrical vibratory gyroscope.](image2)
3. Simulations and Discussion

3.1. Structural and material properties

In the experiment, in order to increase the frequency split reduction, we can increase the depth or diameter of the hole. In order to compare the difference between them and find out the appropriate trimming method, the finite element software is used for simulation analysis. A resonator model has been built as shown in Figure 3. The geometry parameters are listed in Table 1.

![Figure 3. The resonator model.](image)

| Parameters                                      | Value [1] |
|-------------------------------------------------|-----------|
| Height and thickness of resonant ring L and hr   | 8.4 and 1 |
| Height and thickness of suspension ring l and hs | 9.6 and 0.3 |
| Internal radius of resonant R_0                  | 12        |
| External radius of supporting bar r_0            | 4         |
| Thickness of bottom h_b                         | 0.3       |

To validate the effectiveness of trimming measures, a finite element model of gyroscope with defects is needed to simulate the actual situation. Frequency split can be purposefully fabricated by creating several defect blocks Symmetrically distributed at the top of the resonant ring with different density from others [13]. The height and angular width of the defect block are 1400 um and 4º, as show in figure 4.

![Figure 4. The structure of defect block.](image)

The resonator material possesses isotropic and homogeneous properties which are listed in Table 2.
Table 2. Material characteristics of gyroscope.

| Parameters          | Value   |
|---------------------|---------|
| Original Material Density | 8030 kg/m³ |
| Defect Block Density  | 7065 kg/m³ |
| Young’s Modulus      | 210 GPa  |
| Poisson Ratio        | 0.3     |

3.2. Trimming Method

Frequency splitting can be reduced by changing the stiffness or mass in the direction of working mode and its principle can be briefly described by the following equation [13]:

\[
\omega = \sqrt{\frac{k^* + \Delta k}{m^* + \Delta m}}
\]  

(1)

Where \( \omega \) is Eigen frequency of working mode after trimming. \( k^* \) and \( m^* \) are equivalent stiffness and mass of the working mode direction, respectively. \( \Delta k \) and \( \Delta m \) are the stiffness and mass changes of \( k^* \) and \( m^* \) in trimming, respectively.

As show in figure 5, in order to reduce the frequency split, four holes are processed in the mode A or mode B direction by laser. And the trimming holes are located on the middle of the resonant ring.

![Figure 5. The trimming holes.](image)

3.3. Effect of Hole Depth on Frequency Split

The original frequency split is set to 3.50995Hz by modifying the density of defect blocks. In order to reduce frequency splitting, the trimming holes is located in the direction of low frequency mode axis (mode B).

In order to study the effect of hole depth on frequency splitting, a group of simulation experiments (group A) are carried out as follows: the radius of the hole is always 250mm, and the hole depth increases gradually. Simulation results are plotted in Figure 6.
As shown in Figure 6a, with the increase of hole depth, the frequency of mode B (trimming mode) decreases gradually, while the frequency of mode A increases gradually. This causes the frequency split decrease gradually and reach the ideal value when the hole depth is 500μm to 600μm, as shown in Figure 6b. The simulation results show the effectiveness of this method. Negative frequency split indicates that the conversion occurs between high frequency axis and low frequency axis due to over trimming.

There is a good linear relationship between frequency splitting and hole depth. As shown in Figure 6b, the results of linear fitting show that the slope is -0.0061 (Hz/μm), the slope standard deviation is 3.074×10^-4, the intercept is 3.2941 (Hz) and the intercept standard deviation is 0.1286.

### 3.4. Effect of Hole Radius on Frequency Split

The method of reducing frequency split by increasing the hole depth is described above. In fact, a similar effect can be achieved by increasing the radius of trimming hole.

In order to study the influence of hole radius on frequency splitting, the following group of simulation experiments (group B) are carried out: the depth of each hole is set to a constant value: 400μm, and their radiiuses gradually increase. In order to acquire better comparative data between group A and group B, the volume of the holes in group B equal to that in group A at depth of 400μm, 500μm, 600μm and 700μm one by one. Results are plotted in Figure 7.

![Figure 7](image-url)
As shown in Figure 7a, with the increase of the hole radius, the frequencies of mode B (trimming mode) and mode A decrease at the same time, which is different from the simulation results of group A. The frequency reduction of mode B is greater than that of mode a, resulting in the decrease of frequency split, as shown in Figure 7b.

When the depth of the hole is constant, there is also a good linear relationship between the hole radius and the frequency splitting. As shown in Figure 7b, the results of linear fitting show that the slope is \(-0.0037\) (Hz/μm), the slope standard deviation is \(1.935\times10^{-4}\), the intercept is \(1.5662\) (Hz) and the intercept standard deviation is \(0.0567\).

In order to compare the different effects of hole radius and depth on frequency split, the removal mass is used to measure the hole size to plotting the simulation results of group A and group B on one chart, as shown in Figure 8.

$$ya = -2.8790x + 2.4623$$
$$yb = -0.6213 + 1.0403$$

Figure 8. Comparison of frequency split in Group A and Group B.

As show in figure 8, by comparing the trimming methods of increasing the hole depth and radius gradually, we can see that the former method can trim the frequency split to zero faster. Through the linear fitting of the two sets of data, it can be seen that the trimming efficiency is about 2.8790Hz/mg by increasing the hole depth, and 0.6213Hz/mg by increasing the hole diameter. This shows that the effect of the depth of the hole on the frequency split is greater than that of the radius of the hole.

3.5. Effect of Trimming Holes with Different Depth-Diameter Ratio on Frequency Split
In order to further compare the different effects of hole depth and hole radius on the trimming process, group C simulation experiments are carried out: the mass of the hole remained unchanged, and the depth-diameter ratio increased gradually. The simulation results are shown in Table 5 and Figure 9.

$$ya = -2.8790x + 2.4623$$
$$yb = -0.6213 + 1.0403$$

Figure 9. Effect of trimming holes with different depth-diameter ratio on frequency split.
It can be seen that the frequency split decreases with the increase of hole depth-diameter ratio. This shows that trimming holes with larger depth-diameter ratio have higher trimming efficiency. So the effect of hole depth on frequency splitting is greater than that of hole diameter. Therefore, in the actual trimming process, in order to quickly reduce the frequency split, the trimming method of increasing the hole depth can be preferred.

4. Experiments and Discussion

4.1. Experimental Set Up and Method

The size of resonator in experiments is identical with that in simulation. Before the trimming process, the frequency split of the gyroscope is measured. The original working mode frequency is 3585.1213Hz (mode A) and 3585.0359Hz (mode B), and the frequency split is 0.0854Hz.

A laser is employed. By modifying the pulses number and energy, it can remove micro-mass accurately [19]. Such characteristic is advantageous in precise trimming. The experimental set up is plotted in Figure 10. The focal length of the lens is 50mm.

Figure 10. Schematic of experimental set up.

4.2. Trimming Experiments

To reduce the frequency split, the trimming hole is located at the direction of low frequency axis (mode B). As show in Figure 11, four holes are ablated at the top of the resonator. As increasing the hole depth is beneficial to reduce the frequency split quickly, Z-direction feed is added to increase the hole depth as much as possible during drilling.

Figure 11. Ablation holes in experiment.
The experiment was carried out in 8 steps, and each step ablating was in the same position to increase the hole depth. And in each step, laser energy, Z-direction feed and ablation time was increase in order to increase the hole depth.

In order to measure the diameter and depth of the hole to compare with the simulation results, the following methods are used to measure the diameter and depth of the hole: first, the same processing parameters are used on the samples of the same material, and then the samples are cut open to measure the cross section of the hole, as shown in Figure 12.

![Figure 12. Section of ablative hole.](image)

The experimental results are shown in Table 3 and figure 13. Figure 13a shows the relationship between mode frequency and hole depth in trimming process, figure 13b shows the relationship between frequency split and hole depth, and figure 13c shows the relationship between frequency split and hole mass. The mass of trimming hole is calculated as follows:

\[ m = k \cdot \pi r^2 h \]

Where, \( m \) is the mass of trimming hole, \( r \) is the radius of trimming hole, \( h \) is the depth of trimming hole, and the coefficient \( k \) depends on the shape of hole. As the hole is similar to the cone (As show in Figure 12), \( k = 1 / 3 \) is taken.

| Steps | Hole diameter (μm) | Hole depth (μm) | Mass (mg) | Frequency of Mode A (Hz) | Frequency of Mode B (Hz) | Frequency split (Hz) |
|-------|-------------------|----------------|-----------|--------------------------|--------------------------|---------------------|
| 0     | 0                 | 0              | 0         | 3872.602                 | 3870.512                 | 2.090               |
| 1st   | 67                | 327            | 0.003     | 3872.539                 | 3870.626                 | 1.913               |
| 2nd   | 88                | 442            | 0.007     | 3872.531                 | 3870.756                 | 1.775               |
| 3th   | 152               | 494            | 0.024     | 3872.526                 | 3870.811                 | 1.715               |
| 4th   | 205               | 544            | 0.048     | 3872.495                 | 3870.825                 | 1.670               |
| 5th   | 252               | 632            | 0.084     | 3872.456                 | 3870.912                 | 1.544               |
| 6th   | 381               | 1283           | 0.392     | 3872.013                 | 3871.012                 | 1.001               |
| 7th   | 459               | 1707           | 0.756     | 3871.523                 | 3871.012                 | 0.511               |
| 8th   | 500               | 1987           | 1.044     | 3871.093                 | 3870.974                 | 0.119               |

As shown in Figure 13a, with the increase of the hole depth, the frequency of the trimming mode increases gradually, while that of the untrimmed mode decreases gradually. The frequency splitting decreases with the increase of the hole depth, and has a good linear relationship with the hole depth, as shown in Fig. 13b. These results are similar to those in Fig. 6, which shows that the hole depth is an important factor affecting frequency split. Compared with the hole depth, the linear relationship between
the hole mass and frequency split is worse, especially the first several points, as shown in Fig. 13c. This shows that the quality of the trimming hole is not the decisive factor to determine the frequency split.

By linear fitting the data in Fig. 13c, it can be seen that the average trimming efficiency is 1.7065Hz/mg, which is smaller than the trimming method of increasing hole depth in the simulation (2.8790Hz/mg), as shown in Fig. 8. This is because in the experiment, when the hole depth increases, the hole diameter also increases, while in the simulation, only the hole depth is increased. In addition, the difference of hole shape also leads to this result.

The experiment reduces the frequency split from 2.090Hz to 0.119Hz, which verifies the feasibility of this method.

5. Conclusion
In this paper, a method of reducing frequency split by drilling micro-holes using laser was introduced. The influence of the hole diameter and depth on the trimming process was analyzed by finite element software. The simulation results show that the effect of hole depth on frequency split is greater than that of hole diameter. In the trimming process, in order to reduce the frequency split quickly, the trimming method of increasing the hole depth can be preferred.

The experimental results show that the hole depth is an important factor affecting the frequency split. At the same time, the experiment reduces the frequency split from 2.090Hz to 0.119Hz, which verifies the feasibility of the method.
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