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Ultra-precision trimming method for Hemispherical Resonators

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Abstract

The frequency splitting of the hemispherical resonator has a significant impact on its performance, not only affecting the angular rate calculation accuracy of the Hemispherical Resonator Gyroscope (HRG), but also closely related to key indicators such as the gyroscope's stability, repeatability, noise, and scale factor. This paper focuses on the frequency splitting introduced during the processing of the hemispherical resonator, analyzes the frequency splitting mechanism of the hemispherical resonator, builds a vibration characteristic test platform for the hemispherical resonator, and conducts the hemispherical resonator adjustment test in combination with the vibration test results and ion beam processing technology. A resonator with a frequency difference at the mHZ level has been obtained, which is of great significance for improving the research and development and application level of HRG.

Key Words: HRG, Hemispherical Resonator, frequency splitting, ion beam trimming

1. introduction

Hemispherical Resonator Gyroscope (HRG), a type of solid-state vibratory gyroscope, plays a pivotal role in inertial navigation systems due to its exceptional characteristics, including high accuracy, compact size, low mass, simple structure, operational stability, and high reliability[1-3]. The hemispherical resonator, serving as the core component of HRG, exhibits vibration characteristics that predominantly govern the overall performance of the device.

The hemispherical resonator, characterized by its compact dimensions, thin-walled geometry, high brittleness, and elevated hardness, poses significant manufacturing challenges. During fabrication, inevitable machining errors such as thickness non-uniformity are inevitably introduced, thereby inducing frequency splitting. The presence of frequency splitting leads to a degradation in the angular rate calculation accuracy of HRG, ultimately compromising gyroscope performance. Therefore, investigating the mechanisms and suppression of frequency splitting in hemispherical resonators is critical to advancing HRG technology[4].

Frequency splitting primarily arises from mass imbalance within the hemispherical resonator. Consequently, frequency trimming methods for hemispherical resonulators predominantly focus on mass correction, with material removal being the mainstream approach. Current trimming techniques are categorized into four types: Mechanical balancing, Chemical etching, Laser ablation, Ion beam milling[5-7]. Among these, ion beam milling stands out due to its sub-nanometer precision, minimal heat-affected zone, controllable material removal rate, and capability for continuous trimming, making it the most promising technique for high-performance resonators[8].

However, most research on ion beam trimming remains theoretical, with limited experimental implementation. To date, only a few institutions have reported practical applications.Hu Xiaodong et al.[9] utilized ion beam milling to compensate for mass imbalance by analyzing the fourth harmonic component of thickness distribution. After three iterative trimming cycles, frequency splitting was reduced from 0.46 Hz to 0.004 Hz.Yang Yong et al.[10] achieved a reduction in frequency splitting from 0.0581 Hz to 0.0007 Hz through four trimming cycles. However, the specific trimming parameters and experimental datasets were not disclosed, potentially due to technical confidentiality constraints.

While substantial progress has been made in addressing frequency splitting of hemispherical resonators, critical limitations remain: Vibration measurement methodologies[11,12] exhibit room for improvement, particularly in simplifying excitation schemes, enhancing measurement accuracy, and reducing testing cycle durations; Mass balancing techniques generally suffer from insufficient trimming precision or suboptimal post-trimming outcomes. Furthermore, ion beam trimming lacks robust experimental protocols and reproducible datasets to validate its efficacy.

To address these gaps, this study focuses on two primary objectives:Design and implementation of a resonator vibration test platform to optimize excitation methods and vibration characterization workflows; Integration of vibration metrology with ion beam machining to achieve frequency trimming of hemispherical resonators, targeting millihertz-level frequency mismatch post-correction.

This paper takes fused silica hemispherical resonators as the research object. A resonator testing platform is established to achieve mHZ level frequency difference measurements. Ion beam trimming technology is employed to balance the resonators, obtaining devices with excellent frequency splitting performance. The specific contents of each section are as follows: In Section 2, provides a detailed explanation of the frequency splitting measurement methods for hemispherical resonators. A vibration measurement system for hemispherical resonators was constructed, and test protocols for frequency splitting quantification and stiffness axis position determination were developed. In Section 3 verifies the effectiveness of the proposed identification method through experimental measurements of frequency splitting and stiffness axis positions. In Section 4, The removal function of fused silica material is obtained via ion beam bombardment on fused silica planar samples.A hybrid trimming method combining linear ion beam trimming and point-mode trimming is proposed and experimentally implemented.Iterative cycles of measurement and trimming are conducted, ultimately achieving resonators with millihertz-level frequency differences. In Section 5, summarizes the work.

2. Frequency Splitting identification method and system construction

2.1. Frequency splitting identification method

Frequency splitting refers to the phenomenon wherein the four-node vibration mode of a hemispherical resonator during operation resolves into two intrinsic stiffness axes separated by a 45° angle. The natural frequencies along these axes correspond to the maximum and minimum values, respectively, and the difference between these two frequencies defines the frequency splitting [13], as illustrated in Figure 1.

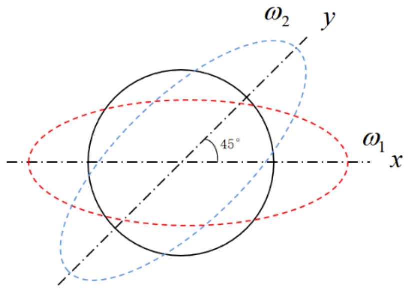


Figure 1. Frequency Splitting Schematic

When the excitation direction is misaligned with the stiffness axes during free vibration of the resonator, the standing wave precesses toward the intrinsic stiffness axes. The vibration pattern at the resonator's periphery can be expressed as:

(1)

(2)

Where x_0 and y_0 are maximum amplitudes in the x and y directions, respectively; t is time; δ is unit impulse function; ω_1 and ω_2 are the angular frequencies of the two frequency splitting axes, respectively.

By synthesizing the directional vibration of two inherently rigid axes, the vibration equation at azimuth ϕ is as follows:

(3)

Considering the Angle ϕ_0 between the standing wave and the normal, the vibration equation can be further reduced to:

(4)

The above equation is the superposition of two simple harmonics. When two simple harmonics with similar amplitude and frequency are superimposed, the amplitude of the synthesized wave will change with the period T, producing a form similar to the beat, which is called the beat frequency. As shown in Figure 2.

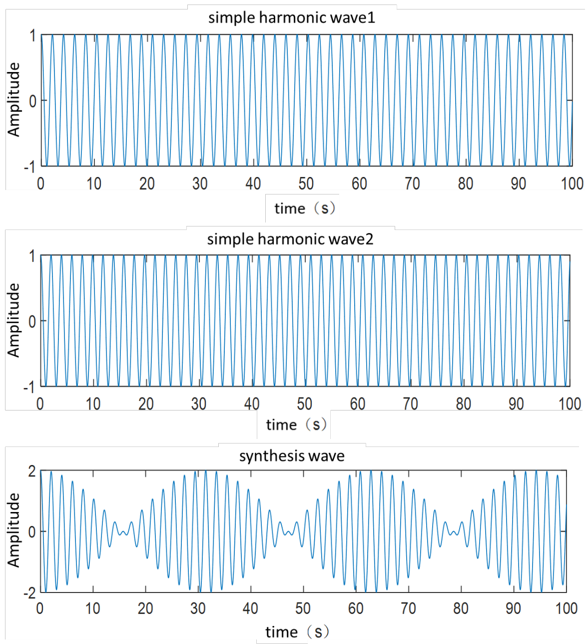


Figure 2. A superposition diagram of waves

Because the frequencies of the two are similar and not equal, there will be a phase difference between the waves, and the amplitude of the two is superimposed when the phase is the same, which is twice the amplitude. When the phase is opposite, the amplitudes of the two cancel out, and there is no vibration. According to the principle of beat generation, the period of beat frequency is only related to the frequency of two simple harmonics, then the period of the synthesized wave is:

(4)

The frequency splitting value of the harmonic oscillator can be obtained by reading the beat period according to the beat signal of the synthesized wave.

2.2. Identification system construction

The hemispherical resonator test platform is composed of computer, signal generator, voltage amplifier, piezoelectric ceramic plate, laser vibrometer, vacuum turntable, vacuum turntable controller, resonator fixture, vacuum chamber, ultra-high vacuum exhaust module, laser Doppler vibrometer, and electronic active vibration isolation platform, as shown in Figure 3.

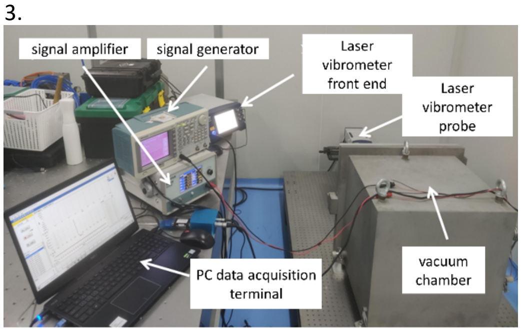


Figure 3. Hemispherical harmonic oscillator vibration test platform

The piezoelectric ceramic is attached to the chassis of the resonator fixture, and the excitation source is a signal generator. The excitation signal is output to the voltage amplifier, and the voltage amplifier then outputs the alternating voltage to the piezoelectric ceramic to complete the excitation of the resonator. This excitation method is convenient to set up and install, simple and accurate control, excellent excitation effect and low cost. The laser Doppler vibrometer is used as the vibration measuring device, which has a very high resolution and the measuring distance can be adjusted without space limitation.

3. Frequency Splitting identification experiment

3.1. Frequency Splitting test

The harmonic oscillator is firmly fixed on the fixture, the piezoelectric plate is fixed on the bottom and side of the fixture, and the fixture is fixed on the vacuum turntable. Adjust the position of laser point irradiation on the lip of harmonic oscillator to ensure maximum amplitude.

Set the software sampling rate to 20kHz and the laser vibrometer's maximum sampling rate to 2.5GHz. Set the signal generator to the sweep mode, the sweep frequency range is 7257Hz-7259Hz excitation resonator, the sweep time is 30s, the sweep frequency interval is 0.1ms, the output signal amplitude is 5Vpp, when the oscillator amplitude is observed to be the largest, stop the excitation, so that it can vibrate freely. The vibration signal is shown in Figure 4, and several beat frequency cycles can be clearly seen.

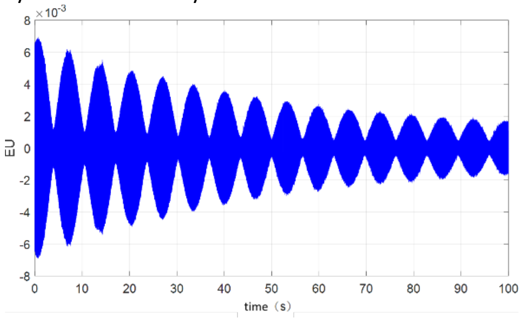


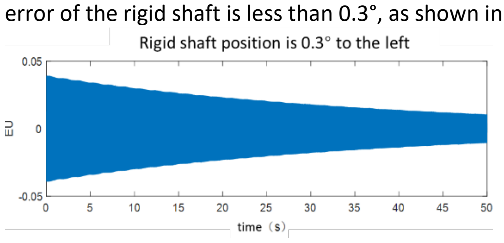
Figure 4. Hemispherical harmonic oscillator beat frequency vibration signal

The figure has a complete 14 beat frequency cycles, beat frequency measurement frequency Splitting the largest error comes from the error caused by inaccurate reading, such reading errors are inevitable, but can be reduced as much as possible, by reading the total duration of all cycles to average the reading error to 14 beat frequency cycles, and then read the total duration of the average number of times. The error can be reduced to a minimum, and finally the frequency Splitting value of the harmonic oscillator is 0.1521Hz.

3.2. Rigid shaft position test

When the vibration measurement position is not on the inherent rigid axis, the collected signal is the beat frequency signal composed of two similar vibration signals. When the vibration measurement position is on the inherent rigid axis, the collected signal is a uniform and freely decayed vibration signal, and the rigid axis position is determined based on this law.

By rotating the harmonic oscillator turntable, the vibration signals at different positions are observed. When the rotation Angle is ±0.3° at the position of the rigid shaft, the beat frequency can still be seen, indicating that the identification error of the rigid shaft is less than 0.3°, as shown in Figure 5.



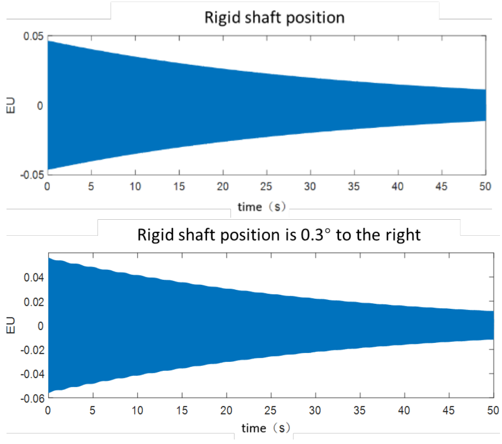


Figure 5. The position of the rigid axis of the hemispherical harmonic oscillator is measured by the beat frequency method

4. Ion beam trimming experiment

The machine tool used in this experiment is the KDIBF ion beam machine tool developed by National University of Defense Technology. As shown in FIG. 6, in order to obtain the removal efficiency of ion beam on fused quartz harmonic oscillator, the fused quartz removal function needs to be known. FIG. 7 is the experimental diagram of fused quartz ion beam removal function. The incident energy of the ion beam is 800eV, and the beam size is 60mA. The fused quartz plate with a diameter of 50mm is processed, and the ion beam bombardment is carried out at four positions with an interval of 20mm, and the removal function is removed for 2 minutes at each point. Finally, the removal function is obtained by the surface shape measurement, and the removal efficiency is $0.15\times10^{-3}mm^3/min$.

Figure 6. KDIBF Ion Beam machine tool

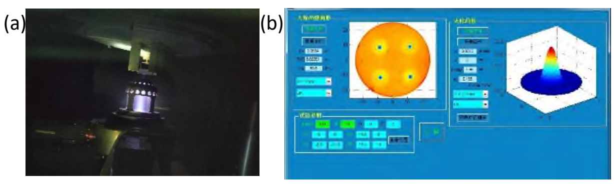


Figure 7. Removal function experiment of ion beam processing of fused quartz. (a) Internal diagram of machine tool during processing. (b) Removal function result.

In order to improve the repair efficiency and reduce the repair positioning error, the ion beam straight-line leveling method is selected to repair the hemispherical harmonic oscillator at the beginning. This method can also avoid the problem of small pits which may be caused by the point repair method due to the large initial frequency difference and long processing time. When the correction result reaches the millihertz level, due to the short processing time, the ion beam sweeps a straight line in a very short time, and the energy is too small to remove the quality, the method of straight line removal and leveling is no longer applicable, and then the ion beam point correction method is used for processing.

Firstly, the frequency Splitting value and low frequency axis position are measured by the hemispherical harmonic oscillator vibration measurement system, and the program is written according to the frequency Splitting value and the size of the ion beam removal function. After the ion beam processing is completed, the measurement and iteration are carried out until the harmonic oscillator frequency Splitting meets the requirements. The experimental diagram of ion beam modification is shown in Figure 8. Since the removal function has a certain width, in order to ensure the integrity of the removal function, the processing is selected at the edge of the harmonic oscillator up 2mm. The linear correction machining shape is a 4mm linear track centered on the position of the low-frequency axis, and four positions are processed with each position covering an Angle of 22.92°. The point correction is to process four low-frequency axis position points. Each time a position is completed, the ion beam is removed, and when the motor is rotated to the next position, the ion beam is moved back to continue processing. The ion beam parameters are set in accordance with the removal function obtained.

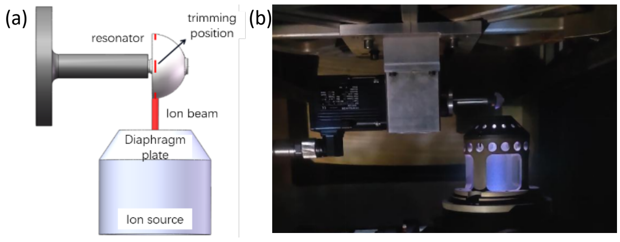


Figure 8. Experimental diagram of ion beam tuning of hemispherical harmonic oscillator. (a) Schematic diagram of ion beam tuning. (b) diagram of actual ion beam tuning process.

When processing is performed at the edge of the harmonic oscillator, the initial frequency difference of the hemispherical harmonic oscillator is small, only 0.0811Hz, so the method of point adjustment is adopted after a linear adjustment. The adjustment results are shown in Table 1. After the last adjustment, the results show that the hemispherical harmonic oscillator can no longer display a complete beat frequency in the complete attenuation time. As shown in Figure 9, when half beat frequency push is observed according to the vibration signal 600s, a beat time is about 1200s, and the frequency Splitting value is about 0.8mHz.

Table 1 Leveling results of hemispherical harmonic oscillator frequency Splitting ion beam

No.	Processing time (s)	Frequency Splitting (HZ)	Mass removal method
1	--	0.0811	--
2	60	0.0127	line
3	5	0.0070	point
4	4	0.0027	point
5	2	0.00083	point

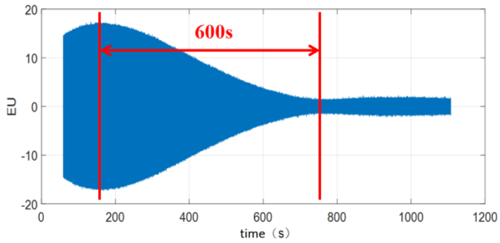


Figure 9. Attenuation waveform when the frequency of the harmonic oscillator is cracked to 0.8mHZ

5. Conclusions

In this paper, an ultra-precise identification and tuning method for frequency Splitting of hemispherical harmonic oscillator is proposed, and ion beam tuning experiments are carried out. The contents are summarized as follows:

1) A hemispherical harmonic oscillator vibration test system is built, and a high-precision frequency Splitting identification method is proposed, which can identify the frequency Splitting value and rigid axis position with high precision, and provide accurate guidance for harmonic oscillator repair.

2) Based on the identification results, a hemispherical harmonic oscillator tuning experiment was carried out in combination with ion beam processing technology. After multiple tuning, the harmonic oscillator frequency Splitting reached 0.8mHz.

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