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Quality factor 와 공진시 변위 측정을 이용한 진동형 자이로스코프의 특성 평가에 관한 연구

전승훈,이준영,정형균,장현기*[1],김용권
서울대학교 전기컴퓨터공학부

A Study on the Measurement Methodology of Characteristics of the Vibratory Micro Gyroscope Using the Quality factor and the Resonant Displacement

Seung-Hoon Jeon, June-Young Lee, Hyoung-Kyoon Jung, Hyun-Kee Chang*[1] and Yong-Kweon Kim
School of Electrical Engineering and Computer Science, Seoul National University

Abstract - In this paper, the new measurement methodology of characteristics of the vibratory micro gyroscope using quality factor and the resonant displacement was proposed. Because the quality factor has a large error under the high quality factor condition, it is difficult to analyze the characteristics of the vacuum packaged vibratory micro gyroscopes with the quality factor. We analyzed mechanical characteristics of gyroscope with the value of quality factor. We described measurement errors of mechanical characteristics of micro gyroscopes. The measured value of quality factor is 47532 and error range of quality factor is from -29.8 % to 73.9 %. The value of resonant displacement is 3.4 μm and the measurement error is 2.9 %. From the result of quality factor degradation and resonant displacement degradation, 1698 days and 1503 days were estimated as Time To Failure (TTF), respectively. The range of estimation error of quality factor degradation and resonant displacement degradation is calculated from 1246 days to 1832 days and from 1456 days to 1537 days, respectively. We can analyze the characteristics of the vibratory gyroscope using the quality factor when the quality factor is smaller than 10,000. Also we can analyze that using the resonant displacement when the quality factor is larger than 10,000.

1. Introduction

Researchers have made extensive studies on improving the resolution of the micro gyroscope. In the vibratory micro gyroscope, one of the methods to improve the performances of the micro gyroscope is operating in the vacuum. A low pressure packaging technique improves the mechanical quality factor because it reduces air damping significantly. [1].

In the vacuum packaged micro gyroscope, the accurate measurement of resonant frequency and bandwidth was needed to analyze mechanical behavior, such as frequency characteristic and dynamic characteristic of the vibratory micro gyroscope. But it is difficult to measure these mechanical characteristics because the measured value of bandwidth is very small and has a large error caused by equipment's resolution under the vacuum condition. The aim of this research is to estimate and analyze mechanical behavior reliably under the high quality factor condition and the low quality factor condition. This paper proposes the measurement methodology of the characteristics of the vacuum packaged vibratory micro gyroscope with the quality factor and the resonant displacement.

2. Theoretical Analysis

Generally, the vibratory gyroscope can be modeled as a two dimensional mass - spring - damp system, as shown in Fig. 1. Assuming linear springs and damping, the basic equations of motion of the gyroscope are given by

$$m_d\ddot{x} + c_d\dot{x} + k_d x = F_0 \sin(\omega t) \quad (1)$$

$$m_s\ddot{y} + c_s\dot{y} + k_s y = 2m_s\Omega\dot{x} \quad (2)$$

where m_d and m_s are the driving mass and the sensing mass, respectively, c_d and c_s damping coefficient of driving mode and sensing mode, k_d and k_s spring constant of driving mode and sensing mode, F_0 the amplitude of driving force, Ω angular rate applying vertically on the surface of the proof mass.

In resonant mode, the small signal response of x can be expressed by

$$|x_s| = \frac{V_p v_d\left(\frac{\partial C}{\partial x}\right)}{\omega_0 c_d} = \frac{V_p v_d\left(\frac{\partial C}{\partial x}\right)Q}{k_d} = \frac{V_p v_d\left(\frac{\partial C}{\partial x}\right)\left(\frac{\omega_0}{BW}\right)}{k_d} \quad (3)$$

where V_p is D.C bias voltage, v_d is A.C signal amplitude, Q and BW are quality factor and bandwidth, respectively. The equation (3) shows mechanical characteristics of the device can be expressed by quality factor, bandwidth, resonant frequency and the resonant displacement in resonant mode. Quality factor has a linear relationship with the resonant displacement.

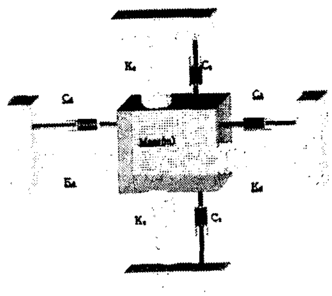

Fig 1. The model of a two dimensional mass spring damp system.

In a high vacuum condition, bandwidth becomes small, thus its small error makes the significant error of quality factor. The quality factor can be expressed by function of bandwidth using the Taylor expansion.

$$Q = \frac{\omega_0}{BW + \Delta} = \frac{\omega_0}{BW}\left(1 - \frac{\Delta}{BW} + \frac{1}{2!}\left(\frac{\Delta}{BW}\right)^2 - K\right) \quad (4)$$

According to Eq. (4), the quality factor is significantly influenced by the error of bandwidth and small value of bandwidth. But the resonant displacement becomes large in a high vacuum condition. Thus, the measurement error of resonant displacement has a small effect on the resonant displacement.

3. Fabrication and Measurement Set Up

3.1 Fabrication Process

The vacuum packaged gyroscope was fabricated for analyzing mechanical characteristics. Fig 2. shows a schematic drawing of the vacuum packaged micro gyroscope. The size of micro gyroscope is 1 cm × 1 cm. The designed quality factor is 1000 in atmospheric pressure. The fabrication process is based on SiOG (Silicon on Glass) process [2]. A feed through hole is penetrated through glass substrate by sand blasting. The electrical connection performed through feed through hole by sputtering Ti/Au (3000 Å). The cover glass was wet etched so as to make a cavity with 150 μm depth. Ti, a getter material is sputtered on a cavity area to improve a vacuum level. Finally, the fabricated cover glass was anodically bonded with SiOG substrate in vacuum environment.

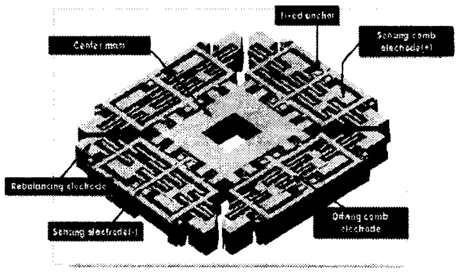

Figure 2. A schematic drawing of the vacuum packaged micro gyroscope

3.2 Measurement Set up

In testing micro gyroscopes, one can use the direct observation of the device under a microscope and the functionality test in the intended mode of operation. Others can detect the signal generated by variation of capacitance of the device in order to measure the displacement amplitude and the frequency response [3,4]. But we used the optical heterodyne small vibro meter measuring equipment (MLD 103) and the dynamic spectrum analyzer (HP 35670A) for measuring frequency and dynamic characteristic. As shown in Fig 3, this system can measure the displacement of the device using retro reflection light from the target. Therefore we need not to concern the critical alignment and the surface diffusivity. The system of dynamic measurement uses power modulated laser light. The light has a 15 μm diameter spot and 1 Hz to 15 MHz response frequency. The measurement resolution of the equipments was determined by frequency sweeping range and sampling number. Maximum sampling number of HP 35670A was 1600. Minimum sweeping range was limited to 100 Hz by the noise signal and the maximum resolution was confined to 0.065 Hz. This resolution is equal to minimal measurement error. To operate the device, we applied 5V bias voltages to micro gyroscope from power supplier and used 0.5V small signal. We obtained the measurement results on frequency response and dynamic response of the device from the dynamic signal analyzer.

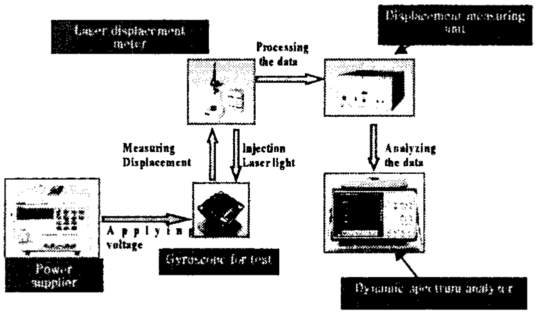

Figure 3. Measurement System for testing the micro gyroscope

4. Measurement Results and Analysis

We measured and analyzed mechanical characteristics of the micro gyroscope under the high quality factor condition. Table 1 shows the measurement results of the mechanical characteristics of three micro gyroscopes.

Table1. Measurement results of mechanical characteristics

	f_n(Hz)	err of f_n(Hz)	BW(Hz)	err of BW
sample #1	7272.43	±0.065	0.153	±0.065
sample #2	8680.00	±0.065	0.53	±0.065
sample #3	8053.44	±0.065	0.965	±0.065

	Q factor	err of Q (%)	X(μm)	err(X)
sample #1	47532	-29.8,+ 73.9	3.4	2.9%
sample #2	16377.4	-10.9,+ 13.9	1.8	5.4%
sample #3	8345.5	-6.3,+ 7.2	1.1	9.9%

The measured resonant frequency and bandwidth of sample #1 were 7272.43 Hz and 0.153 Hz, respectively. The calculated value of quality factor was 47532. When the minimal measurement error (±0.065 Hz) is considered, the exact value of resonant frequency would be ranged from 7272.37 Hz to 7272.50 Hz. And the exact value of bandwidth would be ranged from 0.088 Hz to 0.218 Hz. Thus, from Eq.(4), the quality factors would be calculated to be from 33400 to 82600. The measurement error (0.065 Hz) was 42 % of the measured bandwidth (0.153 Hz), which made large error range of quality factor from 29.8 % to 73.9 %. But as the bandwidth increase, the error of quality factor decrease more quickly. In sample #3, the measured resonant frequency and bandwidth were 8053.44 Hz and 0.965 Hz. This large bandwidth compared that of sample #1 estimate more accurate quality factor with rather small error.

On the other hand, the resonant displacement shows different results. From the results of the dynamic response in resonant mode, resonant displacement was measured. The value of resonant displacement is 3.4 μm, which is the average of five measurement results. The measurement error of resonant displacement is 2.9 %, which is the standard deviation of those results. The error of measured resonant displacement is beneath the one of tenth of resonant displacement, which would represent a few sub micrometers. Because of low damping, the comb structure can vibrate the large amplitude of displacement, which makes rather small error compared that of quality factor. Thus the resonant displacement shows mechanical behavior more accurately under the high quality factor condition. But if the resonant displacement is smaller than 1 micrometers, then it makes large error of measurement results because equipment's noise level is corresponding to 0.1~0.2 μm. Because the resonant displacement has linear relation with quality factor as mentioned in Eq. (3), from the result of Table.1, we can analyze the characteristics of the vibratory gyroscope using the quality factor when the quality factor is smaller than 10,000. Also we can analyze that using the resonant displacement when the quality factor is larger than 10,000.

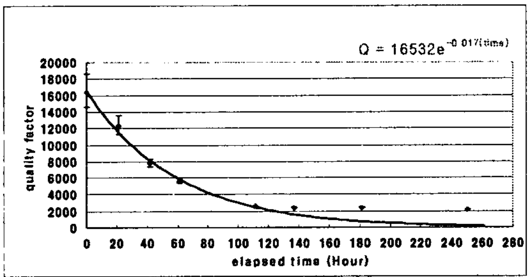

Figure 4. Quality factor degradation as elapsed time (ADT)

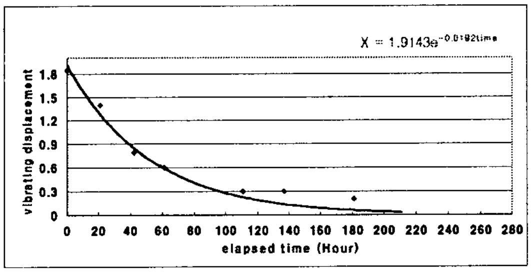

Figure 5. Resonant displacement degradation as elapsed time (ADT)

The result of quality factor degradation was compared with that of resonant displacement by performing an Accelerated Degradation Test (ADT). To conduct ADT, we kept sample #2 in 100℃ environmental chamber and measured the frequency characteristics and dynamic characteristics every 22 hours. Fig. 4 and Fig. 5 show the result of ADT experiment. To estimate the reliability feature, the Arrhenius model was introduced. This model may assume that the degradation proceeds exponentially and has a temperature dependency as given by:

$$L_{ADT}/L_{real} = \exp\left[\frac{\phi}{k}\left(\frac{1}{\theta+273}-\frac{1}{\theta}\right)\right] \qquad (5)$$

where Φ are activation energy, k the Boltzmann constant and Θ temperature(℃) [5]. From the result of quality factor degradation, 1698 days was estimated as Time To Failure (TTF), which means time to take to degrade the 50% of performance. The range of estimation error is calculated to (1246, 1832) days considering the measurement error of the quality factors. But from the result of resonant displacement, 1503 days was estimated as TTF. The range of estimation error is (1456, 1537) days. This range is a lot smaller than that of quality factor degradation. In these results, the measured value of quality factor has very large error under the high vacuum condition. In other hands, the measured value of displacement has rather small error compared that of quality factor. Therefore we can analyze the degradation characteristic of the vacuum packaged micro vibratory gyroscope more accurately by measuring the resonant displacement under the high quality factor condition.

5 Conclusion

We analyzed mechanical characteristics of gyroscope with the value of quality factor. We described measurement errors of mechanical characteristics of micro gyroscopes. From the estimated results, the measured value of quality factor has very large error under the high quality factor condition. In other hands, the measured value of displacement has rather small error compared that of quality factor. But if the resonant displacement is smaller than 1 micrometers, then it makes large error of measurement results. In analyzing the ADT test, more accurate results was obtained by measuring the resonant displacement. Thus we could analyze the mechanical behavior and other characteristics more accurately by measuring the resonant displacement under the high quality factor condition and by measuring the quality factor under the low quality factor condition. This measurement methodology of the characteristics of vacuum packaged vibratory micro gyroscope could be applied to other vacuum packaged vibratory sensors.

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