RESEARCH OF PROCESSING ERRORS ON MODAL FREQUENCY OF A DUAL-MASS DECOUPLED SILICON MICRO-GYROSCOPE

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Abstract In this paper, the architecture, processing errors analysis and optimization method of a dual-mass silicon micro-gyroscope are presented. The dual-mass silicon micro-gyroscope consists of two identical single mass gyroscopes and a lever mechanism. Driving decoupling springs and sensing decoupling springs are key components to achieve motion decoupling. The processing error analysis indicates that the main influence of processing errors on modal frequency are width error of spring beams. The optimization method which increases the width of spring beams is adopted to reduce the effect of width errors on modal frequency. The structure optimization simulation results demonstrate that the frequency difference variation resulting from the processing errors decreased from 53.45% to 7.08% by increasing the width of spring beams.

Introduction

Silicon micro-gyroscopes are novel gyroscopes based on the MEMS technology. The application domain of these sensors is rapidly expanding from automotive to consumer electronics and personal navigation systems. Low cost, small size and easy integration make silicon micro-gyroscopes ideal for use in many fields. There are no MEMS gyroscopes meeting the requirement of inertial-grade, but from the trend in reported gyroscopes we can confirm that inertial-grade gyroscopes will exist in the near future. In order to improve the performance of silicon micro-gyroscope, error sources should be well identified. One of the most important error sources are the processing error.[1]

In this paper, the processing error of a decoupled dual-mass silicon micro-gyroscope is analyzed by ANSYS. Basing on analysis results, we propose an optimization method to decrease the influence of processing error on modal frequency and implement simulation verification.

Principle of decoupled dual-mass silicon micro-gyroscope

A schematic drawing of the micro-gyroscope is shown in Fig .1(a). It consists of two identical single mass gyroscopes, which are connected by driving spring to shape a whole structure. On the top and bottom of the structure, there are two sets of levers in order to suppress the in-phase sensing modal and amplify the anti-phase driving modal. The decouple principle is shown in Fig.1(b). The electrostatic driving force is applied on the driving electrodes. Two driving frames and proof masses on the left and right sides will be driven against each other. Since the stiffness of driving decoupling spring in the driving direction is flexible, sensing frames keep static in driving direction,

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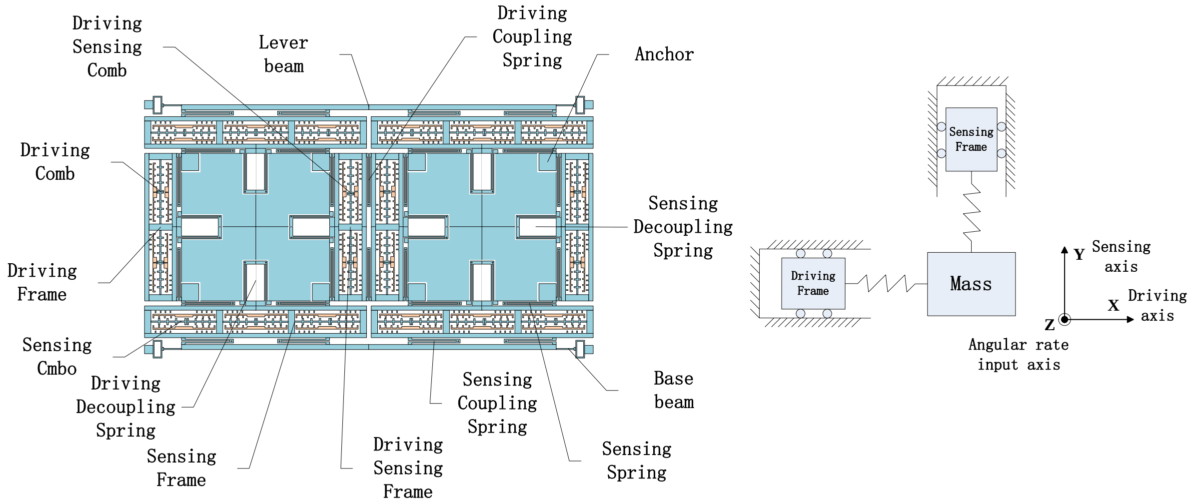
so the driving decoupling will be achieved. When an external angular rate around z-axis is input, two masses are driven into a vibrating motion by the Coriolis forces. Since the stiffness of sensing decoupling spring in sensing direction is flexible, driving frames keep static in sensing direction, so the sensing decoupling will be achieved.



(a) Schematic drawing of a decoupled dual-mass silicon micro-gyroscope (b) decoupling principle of the gyroscope

Fig.1 The structure scheme and decoupling principle of decoupled dual-mass silicon micro-gyroscope

Analysis of spring beam width processing errors

Restricted to the limitations of present processing conditions, the processing error is difficult to be cancelled. Overetching is the common processing error in the fabrication of silicon micro-gyroscopes[2]. Usually in DRIE (Deep Reactive-Ion Etching) process, the etching rate of the silicon structure is closely related to the size of the etched grooves[3]. The narrower groove width is, the slower the etching rate is. Under normal circumstances, comb gap of silicon micro-gyroscope is narrower than the gap of U-shape spring. When the etching of U-shape spring finishes, the gap of comb is still under etching[4]. Therefore, there will be overetching in the U-shape spring when the etching of comb gap is done.

When the width error is Δw, the stiffness of U-shape spring is

$$K_{non-ideal} = \frac{(w+\Delta w)^3 t}{2L^3} \quad (1)$$

The ratio between actual stiffness and ideal stiffness is

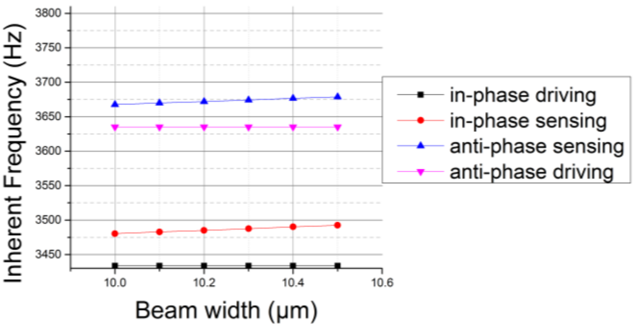
$$\frac{K_{non-ideal}}{K_{deal}} = \left(\frac{w+\Delta w}{w}\right)^3 = \left(1+\frac{\Delta w}{w}\right)^3 \quad (2)$$

Suppose the resonant frequency of silicon micro-gyroscope $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$, the ratio between actual stiffness and ideal stiffness will be

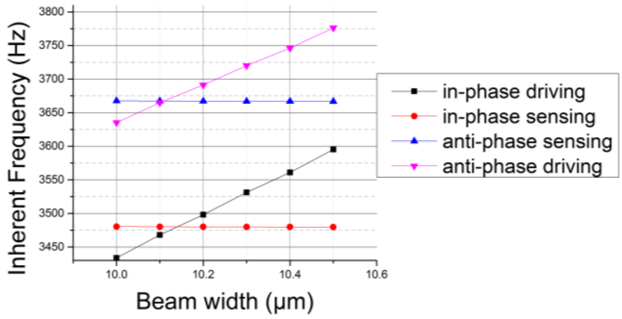
$$\frac{f_{non-ideal}}{f_{ideal}} = \left(1+\frac{\Delta w}{w}\right)^{\frac{3}{2}} \quad (3)$$

Assume the design width of U-shape spring is $10\mu m$ and the design natural frequency is $3000\,Hz$, even if the processing error is only $0.1\mu m$, the change of natural frequency can be $45.11Hz$.

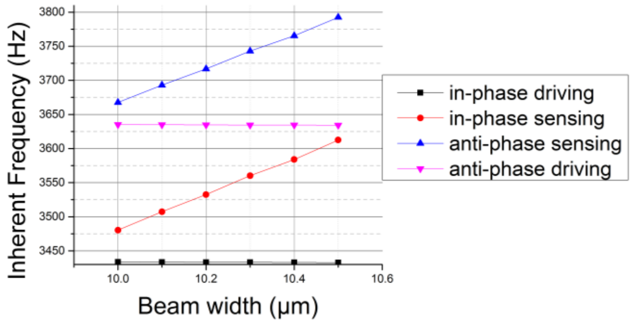
In order to further verify the processing error impact on the gyroscope performance, we use ANSYS to simulate modal and observe the variation of modal frequencies when the width of different U-shape springs changes from $10.0\mu m$ to $10.5\mu m$. In the simulation, U-shape springs in symmetrical position change the width simultaneously. The natural frequencies change of first four modal caused by width error of different springs are shown in Fig.2.



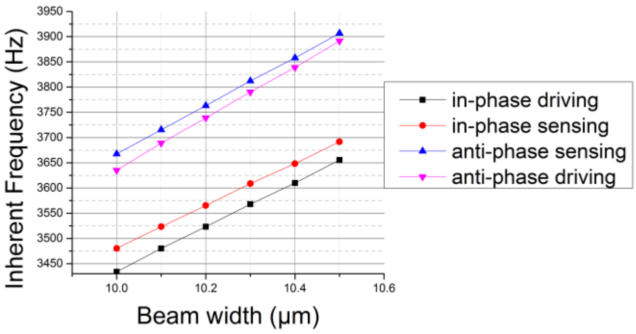
(a) Base beams



(b) Driving decoupling springs



(c) Sensing decoupling springs



(d) All the springs

Fig.2 Effects of different spring width change on the natural frequency of the micro-gyroscope

Fig.3 shows the natural frequency difference between driving mode and sensing mode when the width of different springs change. The width changes of driving decoupling springs and sensing decoupling springs cause the variation of frequency difference of -437.66% and 388.49% respectively and have the biggest impact on the frequency difference. The width errors of base beams result in the frequency difference change of 34.27%. When all the springs width change at the same time, the width change leads to the frequency difference variation of 53.45%.

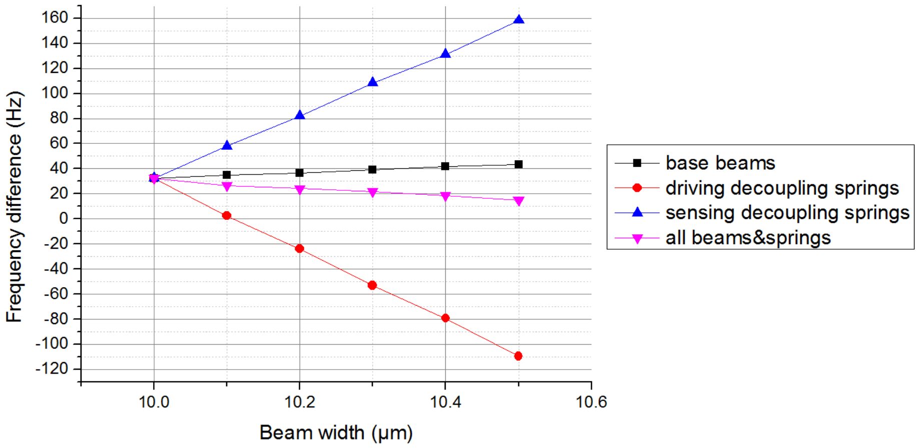
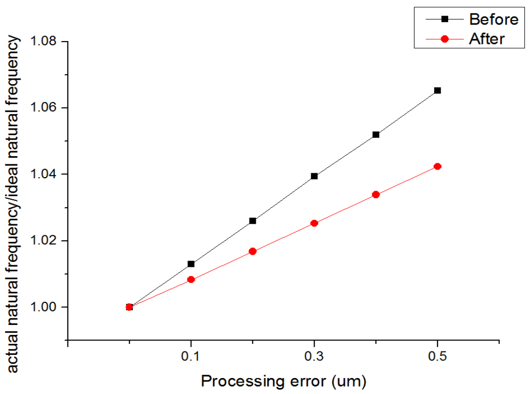


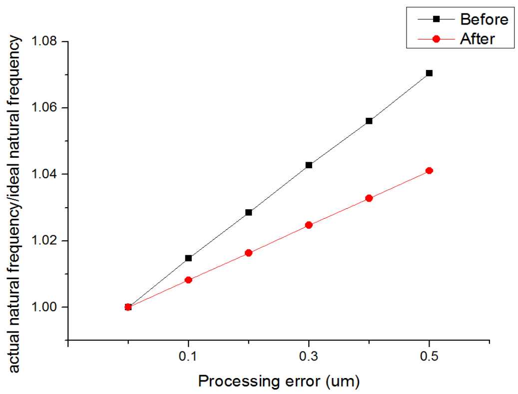
Fig.3 Frequency difference variations of modes when spring width changes

Spring structure parameter optimization and simulation

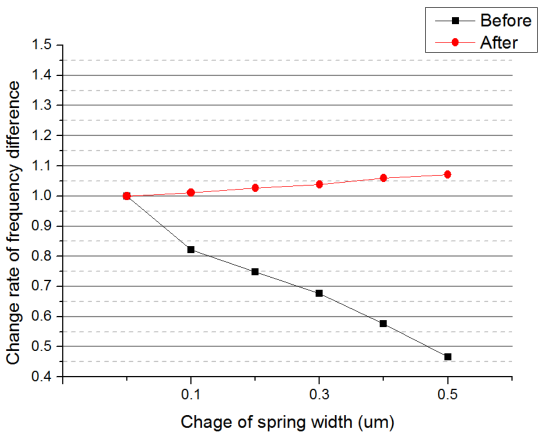
Based on the analysis above, the structure parameter optimization and simulation of dual-mass decoupled silicon micro-gyroscope are implemented to improve the impact of width error on the frequency variation. Beam width of all springs is increased from 10 μm to 15μm and the length is adjusted accordingly. The error step is set as 0.1 μm to conduct analysis. The simulation results are shown in Fig.4.



(a) Changes in natural frequency of anti-driving mode



(b) Changes in natural frequency of anti-sensing mode



(c) Changes in ratio between actual frequency difference and ideal frequency difference

Fig. 4 Comparison of natural frequency and frequency difference of modes before and after structure improvement

By increasing the width of all springs to 15 μm, the influence of processing errors on the variation of micro-gyroscope modes frequency is suppressed compared to the original spring width (10 μm). Table.1 shows the variation rate before and after widening the spring width. Comparing to the original design, the frequency difference variation after the parameter optimization decreases from 53.45% to 7.08% under the same processing errors.

Table.1 Comparison of frequency and frequency difference of operating modes before and after structure improvement

		Anti-phase driving frequency variation	Anti-phase sensing frequency variation	Frequency difference variation
All springs	before	6.52%	6.07%	53.45%
	after	4.24%	4.67%	7.08%

Summary

This paper presents the architecture, processing errors analysis and optimization method of a dual-mass silicon micro-gyroscope. The dual-mass silicon micro-gyroscope consists of two identical single mass gyroscopes and a lever mechanism. The impact of processing errors on mode frequency is analyzed and simulated. The optimization method which increases the width of spring beams is adopted to reduce the effect of width errors on modal frequency. The structure optimization simulation results demonstrate that the frequency difference variation resulting from the processing errors decrease from 53.45% to 7.08% by increasing the width of spring beams.

Acknowledgements

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