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Design of multi-degree-of-freedom micromachined vibratory gyroscope with double sense-modes

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ABSTRACT

This paper presents a novel multi-degree-of-freedom (multi-DOF) micromachined vibratory gyroscope design operated at atmospheric pressure. In this design, the complete 2-DOF vibratory structure is utilized in drive-mode and sense-mode and also, the 2-DOF sense-mode is implemented in both driving frame and proof frame, which form the double 2-DOF sense-modes. The 2-DOF vibratory structure could provide drive-mode and sense-mode with large bandwidth and the double 2-DOF sense-modes could provide high gain of gyroscope system, which improves the inherent robustness and sensitivity simultaneously. The simulation results demonstrate that the summed signal of drive-mode dynamic response is consistent with that of sense-mode and that the gain of proposed multi-DOF micromachined vibratory gyroscope can reach up to −10 dB, increased by above 8 dB compared to the design with single 2-DOF sense-mode. Meanwhile, the 3 dB bandwidth of gyroscope system is larger than 200 Hz.

1. Introduction

The micromachined vibratory gyroscopes have received a lot of attention in the past several decades and some have been designed and implemented in some areas such as automotive, electronics and robots, because compared to conventional gyroscopes, they have the advantages such as small size, low cost, and reduced power consumption. The operation of micromachined vibratory gyroscopes is based on the energy transfer between two quadrature mode, drive-mode and sense-mode, due to Coriolis effect [1]. Since the first micromachined tuning-fork gyroscope was reported by Draper laboratory in 1991, many different 2-DOF micromachined vibratory gyroscope structures have been designed [2–5]. These design mainly utilized 1-DOF drive-mode and sense-mode and improved the sensitivity by mode-matching. But mode matching will often increase quadrature coupling and so these 2-DOF gyroscopes often overcome quadrature coupling through flexural beams and layout of masses [4,5]. However, the 1-DOF drive-mode and sense-mode are susceptible to the structural and environmental parameter variations.

In order to improve the inherent robustness and make micromachined vibratory gyroscopes insensitive to the structural and environmental parameter variations, some multi-DOF vibratory gyroscopes have been presented through increasing DOF of drive-mode or sense-mode [6–8]. In these designs, the 2-DOF dynamic vibration absorber(DVA) structure is utilized to increase the bandwidth of drive-mode or sense-mode and improve the robustness inherently. But the DVA structure limits the structural design space and the tradeoff between die size and detection capacitance [8]. Then the complete 2-DOF vibratory structure is designed instead of the DVA structure [9–11], which could eliminate the limitations of the DVA structure. The complete 2-DOF vibratory structure provides the robust gain-bandwidth frequency region compared to previous gyroscope designs. However, these designs just use the 2-DOF structure in drive-mode or

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sense-mode and the inherent robustness of both modes must be improved through structural design.

A robust 4-DOF micromachined vibratory gyroscope is designed, which uses the DVA structure in both drive-mode and sense-mode [12], but this design is subject to the limitation of DVA structure [8]. Recently, a micromachined vibration gyroscope with complete 2-DOF drive-mode and sense-mode is presented, which utilizes the complete 2-DOF vibratory structure to improve the inherent robustness of drive-mode and sense-mode [13]. This design increases the bandwidth of drive-mode and sense-mode simultaneously and provides robust gain-bandwidth frequency region compared to the conventional 1-DOF vibratory structure. However, the sensitivity is also needed to improve by increasing the mechanical gain of system. For increasing the sensitivity of gyroscope system, the micromachined vibratory gyroscope array is presented, which combines several gyroscope unit by particular layout and link of every gyroscope unit [14].

In this paper, a novel multi-DOF micromachined vibration gyroscope with double 2-DOF sense-mode is proposed to improve both robustness and sensitivity of gyroscope system inherently, which utilizes two 2-DOF sense-modes in driving frame and decoupled frame. As is shown in Fig. 1, the driving frame and decoupled frame form the complete 2-DOF drive-mode and the two 2-DOF sense-mode are linked to driving frame and decoupled frame respectively by proof masses. This design could effectively use the driving frame and decoupled frame to improve the inherent gain of system and isolate vibration between drive-mode and sense-mode through structural design.

The rest of the paper is organized as followed. Section 2 introduces the new design of the multi-DOF micromachined vibratory gyroscope. Section 3 gives the dynamics analysis theoretically in terms of the architecture of the proposed gyroscope and Section 4 describes design principle of the proposed gyroscope. Section 5 reports the related simulation results and Section 6 concludes the paper with a summary of results.

2. Structural design

As is shown in Fig. 1, the gyroscope consists of two 2-DOF sense-modes. The proof mass 1 of sense-mode 1 is suspended in the driving frame and the proof mass 2 of sense-mode 2 is suspended in the decoupled frame, which provide the link between drive-mode and sense-mode. The driving combs are set in the driving frame and the driving force is applied to the driving frame. The sensing-capacitors are set in the detection masses of two sense-modes, which are utilized to pick up the changing capacitance due to Coriolis-induced motion. The two proof masses provide the link between drive mode and sense mode.

The lumped dynamic model of the proposed multi-DOF gyroscope can be simplified as shown in Fig. 2 and both drive-mode and sense-mode are complete 2-DOF dynamic structure. The driving frame m_d and decoupled frame m_f can only oscillate in drive direction (x), which form the complete 2-DOF drive-mode. The two sense-modes are same as each other and they include proof frame m_2 and detection mass m_3, forming the complete 2-DOF dynamic structure. The proof frame m_2 and detection mass m_3 could only oscillate in sense direction y, but the proof masses m_1 could move in both drive direction and sense direction.

When the proposed multi-DOF micromachined vibratory gyroscope is operated, the harmonic driving force F_d is applied to the driving frame m_d to force the driving frame m_d and the decoupled frame m_f (with the respective proof masses) to oscillate in drive direction (x). When an angular rate perpendicular to the x–y plane is input, the Coriolis-induced force is applied to the proof masses m_1, which drives the proof mass m_1 (with proof frame m_2) and the detection mass m_3 to move in sense direction (y). Then the Coriolis-induced motion is picked up by the detection mass m_3. Unlike previous multi-DOF micromachined vibratory gyroscopes [9,13,15], the proposed multi-DOF micromachined vibratory gyroscope not only utilizes a fully coupled 2-DOF vibratory structure in both drive-mode and sense-mode, but also uses the double 2-DOF sense-modes.

In this design, the proof masses m_1 could oscillate in both drive mode and sense mode so that the driving frame m_d, decoupled frame m_f, proof frame m_2 and detection mass m_3 just move in only one direction, drive direction or sense direction. Then the movements of driving combs in drive mode and sensing-capacitors in sense mode will have no effect on each other, which isolates the vibration between drive mode and sense mode.

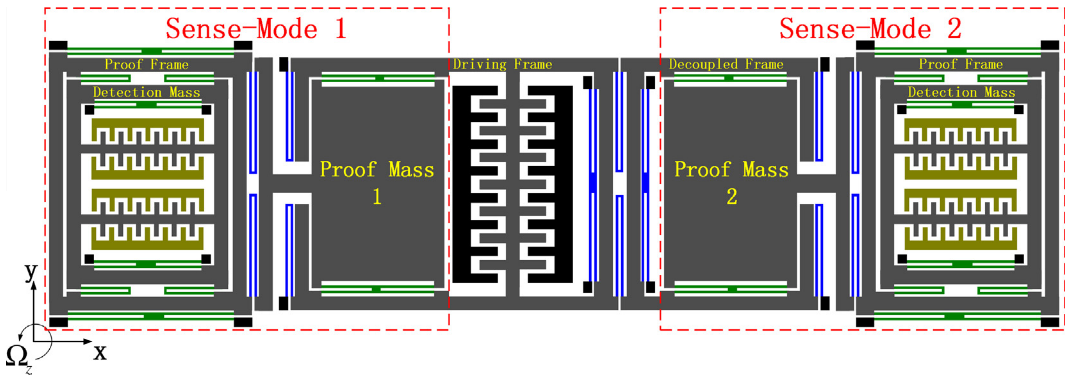

Fig. 1. Schematic of the proposed multi-DOF micromachined vibratory gyroscope.