Inherently Robust Micromachined Gyroscopes with 2-DOF Sense-Mode Oscillator

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***Abstract*— Commercialization of reliable vibratory micromachined gyroscopes for high-volume applications have proven to be extremely challenging, primarily due to the high sensitivity of the dynamical system response to fabrication and environmental variations. This paper reports a novel micromachined gyroscope with 2 degrees-of-freedom (DOF) sense-mode oscillator, that provides inherent robustness against structural parameter variations. The 2-DOF sense-mode oscillator provides a sense-mode frequency response with two resonant peaks and a flat region between the peaks, where the amplitude and phase of the response are insensitive to parameter fluctuations. Furthermore, the sensitivity is improved by utilizing dynamical amplification of oscillations in the 2-DOF sense-mode oscillator. Prototype gyroscopes were fabricated using a bulk-micromachining process, and the performance and robustness of the devices have been experimentally evaluated. With a 5.8μm drive-mode amplitude, the tested unit exhibited a measured noise-floor of 0.64^0/s/$\sqrt{\mathrm{Hz}}$ at 50Hz bandwidth in atmospheric pressure. The sense-mode response in the flat operating region was also experimentally demonstrated to be inherently insensitive to pressure, temperature and DC bias variations.**

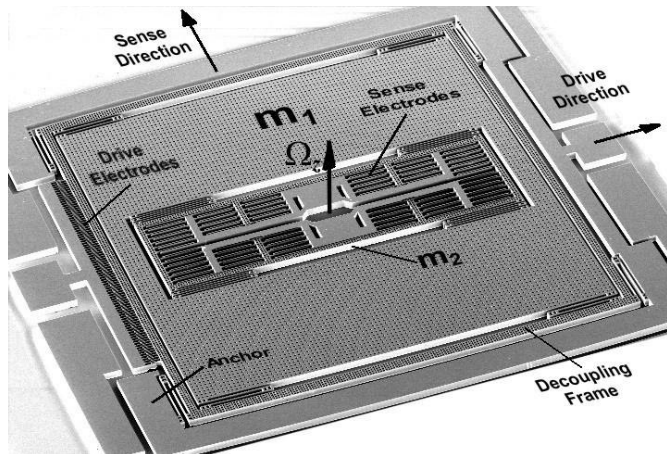

Fig. 1. Scanning electron micrograph of the prototype bulk-micromachined 3-DOF gyroscope with 2-DOF sense-mode. The die size is approximately 4mm x 4mm .

I. Introduction

Inspired by the promising success of micromachined accelerometers, extensive research efforts towards commercial micromachined gyroscopes led to several innovative gyroscope topologies, fabrication and integration approaches, and detection techniques. Consequently, vibratory micromachined gyroscopes that utilize vibrating elements to induce and detect Coriolis force have been proven to be effectively implemented and batch fabricated in different micromachining processes [1]. However, achieving robustness against fabrication variations and temperature fluctuations remains one of the greatest challenges in commercialization and high-volume production of micromachined vibratory rate gyroscopes.

In most of the reported MEMS gyroscopes, a one degree-of-freedom (1-DOF) sense-mode oscillator is employed, and the device is operated at resonance in the drive-mode. Typically, the sense-mode resonance is designed to be slightly shifted from the drive-mode in order to improve bandwidth, robustness, and stability; while intentionally sacrificing gain and sensitivity. Yet, the response amplitude and phase of the resulting mechanical system remains extremely sensitive to the relative location of the drive and sense resonant frequencies. The inadequate tolerancing and critical dimension control capabilities of the current photolithography processes and micro-fabrication techniques lead to drastic variations in oscillatory system parameters. Thus, the resulting fabrication variations and imperfections that shift the natural frequencies impose strict requirements for the active feedback control system and the detection electronics [2], [3].

This paper presents a novel structural design concept for micromachined gyroscopes that provide inherent robustness against structural and environmental parameter variations. The emphasis is on investigating the paradigm of shifting the complexity from the control electronics to the structural design of gyroscope dynamical system. The design approach explores the possibility of achieving a wide-bandwidth frequency response in the sense-mode of the vibratory gyroscopes. Thus, the disturbance-rejection capability is achieved by the mechanical system instead of active control and compensation strategies [4]. The micromachined gyroscopes of this class could potentially yield reliable, robust and high performance angular-rate measurements leading to a wide range of high-volume applications including dynamic vehicle control, automotive safety systems, navigation/guidance systems, and interactive consumer electronics.

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II. The 3-DOF MEMS Gyroscope Structure

The presented design concept addresses the following major MEMS gyroscope design challenges: 1) The requirement of precisely controlling the relative location of the drive and sense resonance modes from device to device, and within the required temperature range; 2) Variation in the Coriolis signal phase due to the shift in natural frequencies; 3) Long-term variation in sensitivity due to package pressure degradation.

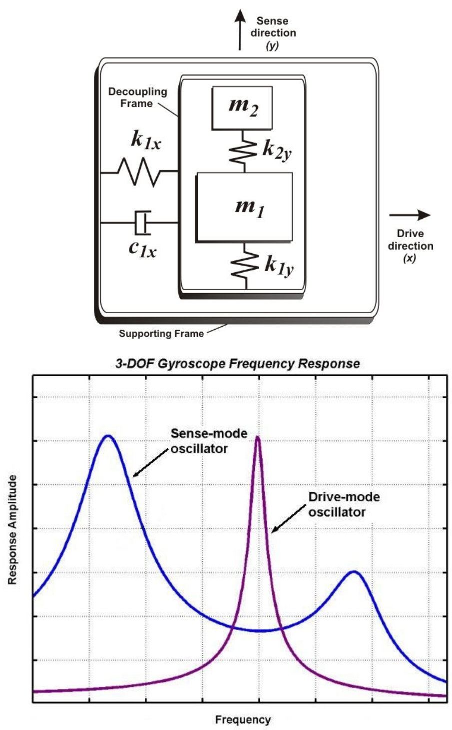

Fig. 2. Lumped mass-spring-damper model and the frequency response of the overall 3-DOF gyroscope with 2-DOF sense-mode.

The proposed gyroscope dynamical system consists of a 2-DOF sense-mode oscillator and a 1-DOF drive-mode oscillator (Figure 1). The first mass, m_1, is free to oscillate both in the drive and sense directions, and is excited in the drive direction. The second mass, m_2, is constrained in the drive direction with respect to the first mass. In the drive-direction, m_1 and m_2 oscillate together, and form a resonant 1-DOF oscillator. The smaller proof mass m_2 forms the passive mass of the 2-DOF sense-mode oscillator (Figure 2), and dynamically amplifies the sense mode oscillations of m_1.

The 2-DOF sense-mode oscillator provides a frequency response with two resonant peaks and a flat region between the peaks, instead of a single resonance peak as in conventional gyroscopes (Figure 2). The device is nominally operated in the flat region of the sense-mode response curve, where the gain is less sensitive to variations in the natural frequencies and damping. Thus, reduced sensitivity to structural and thermal parameter fluctuations and damping changes are achieved, leading to improved stability and robustness against environmental and fabrication variations.

Furthermore, the sensitivity is improved by utilizing dynamical amplification of oscillations in the 2-DOF sense-mode oscillator. The smaller mass m_2 is employed as the sensing mass, and the larger mass m_1 generates the Coriolis force that excites the 2-DOF sense-mode oscillator. For a given Coriolis force, the amplitude of the sensing mass m_2 increases with decreasing ratio of the proof masses m_2/m_1, which dictates minimizing the mass of m_2 and maximizing the mass of m_1. Also, it is desired that a large Coriolis force is induced on m_1, which also dictates maximizing the mass of m_1. With these two aligning design constraints, the concept could potentially yield better sensitivity than a conventional gyroscope with mismatched modes; while providing enhanced robustness.

Since the gyroscope structure oscillates as a 1-DOF resonator in the drive direction, the drive-mode frequency response has a single resonance peak, and the device is operated at resonance in the drive-mode. Thus, the flat region of the sense-mode oscillator is designed to coincide with the drive-mode resonant frequency. This allows utilization of well-proven drive-mode control techniques, while providing robust gain and phase in the sense-mode.

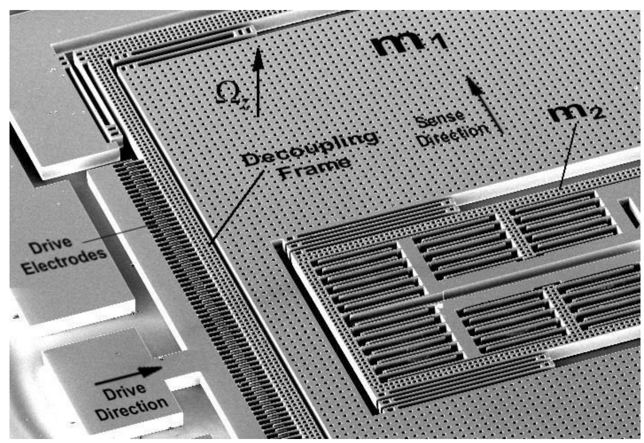

Fig. 3. The frame implementation for decoupling the drive and sense-mode oscillations of m_1.

Fabrication imperfections also introduce small imbalances and asymmetries in the gyroscope suspension structure, causing dynamic cross-coupling between the drive and sense directions often much larger than the Coriolis motion [5]. In the 3-DOF gyroscope structure, the drive and sense direction oscillations of m_1 can be mechanically decoupled to a great extent by using a unidirectional frame structure, in order to minimize quadrature error due to anisoelasticities and to suppress undesired electrostatic forces in the sense-mode due to drive-mode actuator imperfections. When m_1 is nested inside a drive-mode frame (Figure 3), the sense-direction oscillations of the frame are constrained, and the drive-direction oscillations are forced to be in the designed drive direction. Since m_1 is free to oscillate only in the sense-direction with respect to the frame, the sense-mode response of m_1 becomes perfectly orthogonal to the drive-direction.

III. Bulk-Micromachined Prototype Fabrication

Prototype 3-DOF gyroscope structures were fabricated in the UCI Integrated Nano-Systems Research Facility using a one-mask bulk-micromachining process, based on deep-reactive ion etching through the $100\mu m$ device layer of silicon-on-insulator wafers. The DRIE process was performed in an STS ICP. In the device, $15\mu m \times 15\mu m$ holes were used to perforate the suspended structures, in order to allow front-side release of the structures by etching the Oxide layer in HF solution. The anchors were designed as unperforated areas larger than $40\mu m \times 40\mu m$ for 25 min release in 49% HF solution, defining the structural layer and the anchor layer using one mask.

IV. Experimental Analysis of Parametric Sensitivity

The frequency response of the 2-DOF sense-mode oscillator was characterized electrostatically under various environmental conditions in an MMR vacuum probe station. A test gyroscope structure similar to the 2-DOF sense-mode oscillator of the gyroscope, but with actuation electrodes attached to the sense-mode active mass m_1 was designed and characterized. The frequency response was acquired using off-chip transimpedance amplifiers with a feedback resistor of R_A=1MΩ connected to a signal analyzer in sine-sweep mode.

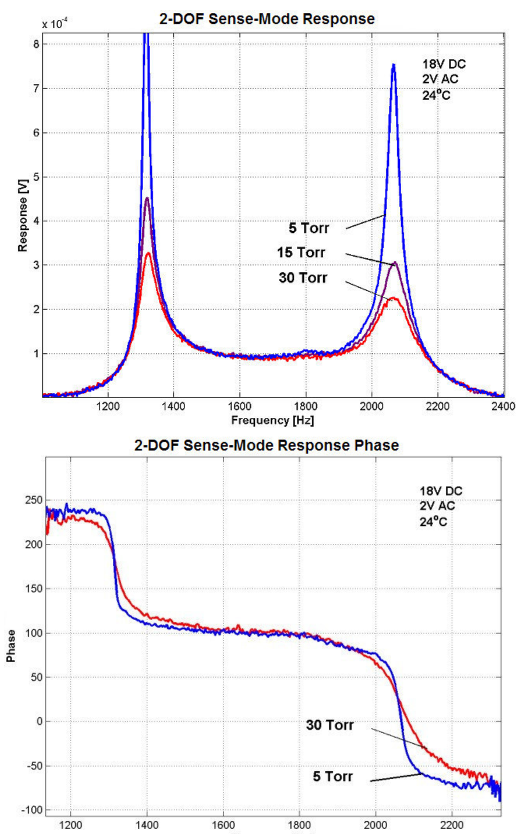

Fig. 4. Electrostatically acquired amplitude and phase response, with changing pressure values. The amplitude and phase of the response remains constant within the flat region.

A. Pressure Variations

Figure 4 presents the experimentally measured amplitude and phase responses of the sense-mode passive mass at 5, 15, and 30 Torr. The oscillation amplitude in the two resonance peaks were observed to increase with decreasing pressures. However, the change in the response amplitude in the flat operating region is insignificant, experimentally demonstrating the damping insensitivity of the sense-mode response in the flat operating region. Furthermore, the phase of the sense-mode passive mass was observed to stay constant in the operating frequency band, while the phase changes were observed at the two resonance peaks (Figure 4). Thus, it is experimentally verified that a constant-phase response is achieved in the operating region, in contrast to the abrupt phase changes near the resonance peaks.

B. Temperature Variations

The sensitivity of the 2-DOF oscillator to temperature variations was characterized by heating the vacuum chamber, and continuously monitoring the temperature of the sample using a solid-state temperature sensor attached to the substrate. Figure 5 presents the capacitively acquired frequency response of the sensing element at the temperatures 25^{o}C and 75^{o}C. The maximum amplitude variation in the flat operating region was observed to be less than 2% for the 50^{o}C increase in temperature, experimentally verifying the improved robustness against temperature variations.

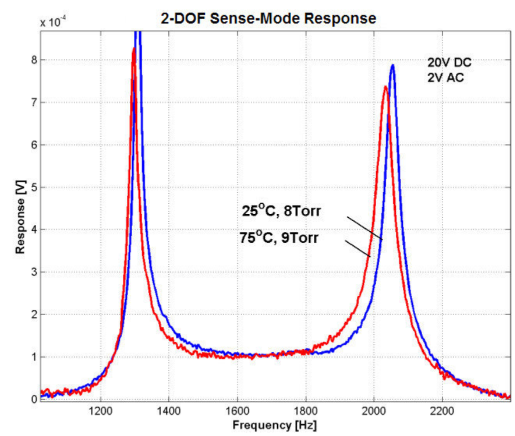

Fig. 5. The frequency response of the sense-mode passive mass, at 25^{o}C and 75^{o}C. The response gain within the flat operating region is observed to stay constant.

C. Electrostatic Tuning

In order to observe the effects of larger stiffness variations on the system response, the frequency response of the sense-mode passive mass was acquired with different DC bias voltages. Figure 6 presents the experimental frequency response measurements for 18V to 21V DC bias at 4 Torr pressure. The electrostatic negative spring effect was observed to result in 30Hz shift in the first resonance peak and 45Hz shift in the second resonance peak, however, normalized amplitude in the flat operating region was observed to change insignificantly.

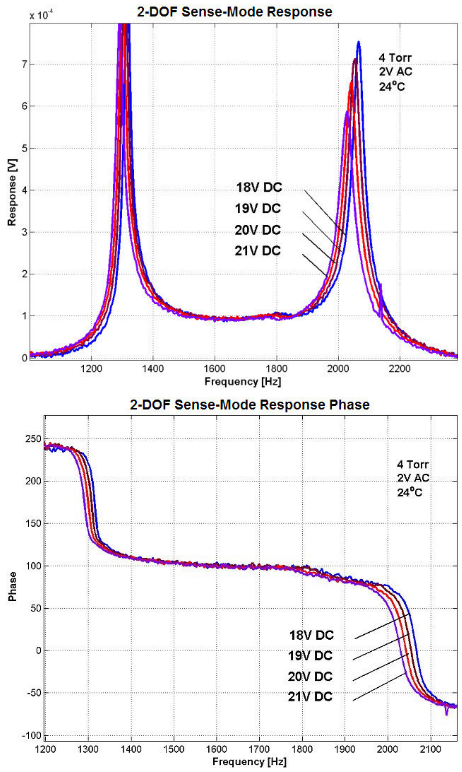

Fig. 6. Electrostatically detected amplitude and phase response of the sense-mode passive mass, with changing DC bias.

V. Rate-Table Characterization

Synchronous demodulation technique was used to extract the angular rate response of the 3-DOF gyroscope. The device was operated at resonance in the drive-mode with a 25V DC bias and 3V AC drive signal. The drive-mode amplitude was measured optically during the operation of the device as 5.8μm, using a microscope attached to the rate-table platform. A 20kHz carrier signal was imposed on the gyroscope structure, and the output from the differential sense-capacitors was amplified outside the package and synchronously amplitude demodulated at the carrier signal frequency using a lock-in amplifier. The Coriolis signal was finally demodulated at the driving frequency. With this technique, a sensitivity of 0.0308 mV/$^0/$s was experimentally demonstrated while the device was operated in the flat-region of the sense-mode frequency response. The measured noise floor was 19.7 μV/$\sqrt{\mathrm{Hz}}$ at 50Hz bandwidth, yielding a measured resolution of 0.64$^0/$s/$\sqrt{\mathrm{Hz}}$ at 50Hz bandwidth in atmospheric pressure. The resolution could be drastically improved by utilizing preamplifiers or complete detection electronics inside the device package.

In order to verify that robustness to parameter variations is achieved in the overall Coriolis response, the 3-DOF gyroscope was characterized on the rate table in a thermally controlled chamber. The temperature of the gyroscope was increased from 25^{o}C to 75^{o}C while manually tracking the drive resonance frequency to restore the drive amplitude to 5.8μm. The sensitivity at 75^{o}C was measured as 0.0303 mV/$^0/$s, with only 1.62% change in uncompensated sensitivity, experimentally verifying the improved robustness. At elevated temperatures, the linearity of the response was also observed to be preserved.

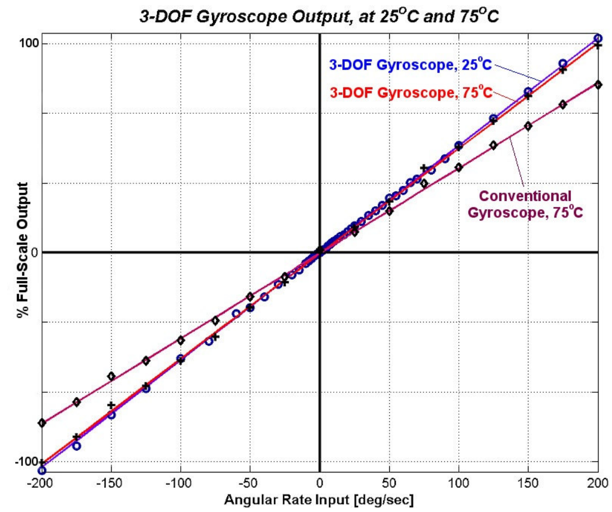

Fig. 7. The measured angular-rate response of the 3-DOF gyroscope and a conventional gyroscope at 25^{o}C and 75^{o}C.

When a conventional gyroscope with a 1-DOF sense-mode fabricated on the same wafer was characterized using the same signal conditioning electronics, the sensitivity was observed to drop from 0.91 mV/$^0/$s to 0.73 mV/$^0/$s for the same 50^{o}C temperature increase. The observed 19.8% sensitivity change in the conventional gyroscope is over 12.2 times larger than the 3-DOF gyroscope approach.

VI. Conclusion

This paper presented a 3-DOF gyroscope system with 2-DOF sense-mode oscillator, which significantly suppresses the effect of parameter variations on the gain and phase of the sense-mode response, while compatible with well-proven drive-mode control techniques. The in-house fabricated bulk-micromachined prototypes were successfully operated as a gyroscope in the flat region of the sense-mode response. The prototype gyroscope exhibited a measured noise-floor of 0.64$^0/$s/$\sqrt{\mathrm{Hz}}$ over 50Hz bandwidth in atmospheric pressure. The sense-mode response in the flat operating region was also experimentally demonstrated to be inherently insensitive to pressure, temperature and DC bias variations.

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