Integrated Surface-Micromachined Z-axis Frame Microgyroscope

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ABSTRACT

We report the first integrated surface-micromachined z-axis frame microgyroscope fabricated in the Analog Devices Modular-MEMS process using 6µm thick polysilicon as the structural material and 5V 0.8µm CMOS process. This vibratory microgyroscope, which operates in vacuum, measures the z-axis rotation rate by sensing the induced Coriolis acceleration using capacitive sensing. The amplitude of drive motion was estimated to be 2µm. The frame gyroscope mechanically decouples the drive and sense motion for stable operation. Integration of circuits and mechanical structures on the same substrate allowed signal sensing with low parasitics. The surface micromachined integrated z-axis frame gyroscope fabricated at Analog Devices has a measured noise floor of 0.05 deg/s/√Hz and a scale factor of 0.33 mV/deg/sec at 70 milli-Torr ambient pressure.

INTRODUCTION

Microgyroscopes offer several advantages such as low cost, miniature size, and low power requirements for many applications ranging from automotive industry to inertial measurement units. On top of that, monolithic integration of surface-micromachined structures with driving, sensing and signal processing electronics is highly desirable as they can benefit from increased signal-to-noise ratios and reduced manufacturing costs. This integration was demonstrated in this work with the implementation of the first integrated surface-micromachined z-axis frame microgyroscope fabricated in the Analog Devices Modular-MEMS process [1]. Such integration will enable multi-sensing chips and could lead to single chip inertial measurement unit.

Microgyroscopes are sensors commonly used to sense angular motion about one or more axes. Vibratory micromachined gyroscopes work on the principle of detecting the induced Coriolis acceleration on the proof mass that is driven in an orthogonal direction to the applied input rotation rate [2]. Various sensing techniques [3] have been demonstrated to estimate the Coriolis force, and hence the rotation rate, by measuring the displacement of the proof mass in the sense direction which is orthogonal to the driven direction. Hence, it is necessary that the suspended proof mass is compliant in two orthogonal directions.

For simplicity, the same resonating mass can be used for sensing of the Coriolis-induced displacement. However, this design is prone to coupling between drive and sense modes [4-5]. When the modes are closely matched, which is usually desired to maximize sensitivity, this coupling causes unstable operation. In addition, the fact that the typical drive motion amplitude is 5-6 orders of magnitude larger than the sense motion makes the single mass gyroscope prone to large output errors. As a substitute for single mass gyro, frame gyroscope capable of decoupling the drive and sense motions for stable operation and to reduce output errors [4-5] has been demonstrated.

PRINCIPLE OF OPERATION

Fig. 1 shows an example of frame gyroscope that has a drive mass (inner mass) and a sense mass (outer frame) compliant in x and y directions respectively suspended by mechanical springs.

![Frame gyroscope](image)

Figure 1: Frame gyroscope

Lateral comb fingers are used to drive the inner mass (drive mass) into resonance. During the drive motion, only the drive mass oscillates along the x-axis since the sense spring is stiff in the direction. The drive resonant frequency is given by

\[ \omega_x = \sqrt{\frac{k_d}{m_d}} \]

where \( k_d \) = drive spring constant
In the presence of an input rotation rate about z-axis, the driven mass will experience Coriolis force, proportional to velocity of drive motion and its mass, along the y-axis (sense motion). This force causes both masses to move along the sense axis. The drive and sense modes are shown in Fig. 2. The sense resonant frequency is given by

$$\omega_y = \sqrt{k_s/(m_d + m_s)}$$  \hspace{1cm} (2)

where $k_s$ = sense spring constant

Drive and sense spring constants depend on the dimensions of the mechanical springs and the material’s Young’s Modulus. Parallel plate capacitors are then used to detect this sense displacement.

![Figure 2: (a) Drive mode, (b) Sense mode](image)

The ratio of measured sense displacement along y-axis ($\Delta y$) to the rotational rate ($\Omega_z$) can be expressed as

$$\frac{\Delta y}{\Omega_z} = \frac{2X_o \omega_x}{\omega_y^2 - \omega_x^2 + j \omega_y \omega_x / Q_y}$$  \hspace{1cm} (3)

assuming sinusoidal drive motion with an amplitude of $X_o$. $Q_y$ represents the quality factor along the sense axis. To maximize the sense displacement and thus, the sensitivity of device, matched mode operation in vacuum is desired. Matched mode operation minimizes the difference ($\omega_y - \omega_x$) while vacuum operation maximizes $Q_y$.

Sense mode tuning combs are used to tune the sense resonant frequency to achieve sufficient mode matching for improved resolution and sensitivity.

Figure 3 shows the closed loop drive circuit using a transresistance amplifier with Automatic Gain Control (AGC). If the transresistance amplifier has sufficient gain among other conditions, the proof mass will be driven into oscillation at its natural frequency ($\omega_x$). The amplitude of oscillation, which can be controlled using the AGC, is critical in maintaining the proof mass oscillation in linear region and to accurately determine the scale factor for the device. There were some off-chip components in AGC.

![Figure 3: Close-loop drive circuit with AGC](image)

The Coriolis acceleration is detected using parallel plate capacitive sensing technique. A differential sense circuit, Fig. 4, was used to detect the change in sense capacitance.

![Figure 4: Differential sense circuit](image)

**DEVICE FABRICATION**

Integrated frame gyroscopes were fabricated in the Analog Devices Modular-MEMS process reaping the benefits of circuit integration with the sensor and the advantages of frame suspension for a gyroscope. Figure 5 briefly describes the process flow in this MEMS-first modular process. In this process, 6µm thick polysilicon is used as the structural layer that reduces out-of-plane motion, which is critical for z-axis gyroscope. Another polysilicon layer underneath the structural layer is used to shield the structure from the substrate reducing parasitic capacitances or to make electrical contact from the structure to the circuit. 5V CMOS driving and sensing circuits are fabricated right next to the structures minimizing the interconnect parasitics.
RESULTS AND DISCUSSION

Figures 6 and 7 show the die shot of the fabricated device and the close-up of the gyro mechanical structure respectively. The chip (3.5mm x 3.5mm) was wire bonded to a 40-pin DIP package for experimental testing.

The lateral comb drive fingers and the parallel plate sense combs are clearly visible in Fig. 7. The close-up of some combs fingers is shown in Fig. 8. Etch holes found on the proof mass were necessary to completely etch the sacrificial oxide layer underneath the proof mass.
The drive mass resonated when a proof mass voltage of 8.2V is applied at about 70mTorr. Figure 9 shows the spectrum of the drive output. Drive frequency was observed to be 18.7kHz, which agreed with theory. Amplitude of drive oscillation was estimated to be about 2µm. For rate testing, the device was placed in a portable vacuum chamber mounted on a rate table.

Figure 9: Spectrum of drive output

A 10 Hz sinusoidal rotation rate about z-axis with amplitude of 15deg/sec was applied to the device through the rate table. Figure 10 shows the spectrum of the sense circuit output. The signal at 18.7 kHz represents the Coriolis offset, quadrature and the feedthrough signal. The 2 sidebands represent the rotation rate signal.

Figure 10: Sense output with 10Hz sinusoidal input rotation rate signal

Sensitivity of device was measured to be 0.33 mV/deg/sec as shown in Fig. 11. This prototype device exhibited a noise floor of about 0.05deg/s/√Hz limited by electronic noise.

CONCLUSION

An integrated z-axis frame gyroscope fabricated in the Analog Devices Modular-MEMS process was described. Frame gyroscope design decouples the drive and sense motion for stable operation. Closed loop drive with AGC enabled the drive amplitude to be controlled and hence, determine the scale factor accurately. Integration of CMOS circuits with the mechanical structures reduces the interconnect parasitics and hence, the noise floor of the device. A prototype device fabricated in MOD-MEMS process exhibited a noise floor of 0.05deg/s/√Hz.

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