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Scale Factor Determination of Micro-Machined Angular Rate Sensors Without a Turntable

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Abstract: This paper presents a digital readout system to detect small capacitive signals of a micro-machined angular rate sensor. The flexible parameter adjustment ability and the computation speed of the digital signal processor were used to develop a new calibration procedure to determine the scale factor of a gyroscope without a turntable. The force of gravity was used to deflect the movable masses in the sensor, which resulted in a corresponding angular rate input. The gyroscope scale factor was then measured without a turntable. Test results show a maximum deviation of about 1.2% with respect to the scale factor determined on a turntable with the accuracy independent of the manufacturing process and property variations. The calibration method in combination with the improved readout electronics can minimize the calibration procedure and, thus, reduce the manufacturing costs.

Key words: scale factor; micro-machined angular rate sensor; gyroscope; calibration; digital readout

Introduction

Micro-machined angular rate sensors or gyroscopes are used to measure the angular velocity of a moving object without an external reference. Low cost, high precision gyroscopes find a large market in consumer products, automobiles, medical equipment, military equipment, industrial equipment, and other applications[1]. Due to this large market, many research groups and companies[2] are working on the design and fabrication of the manufacturing processes, readout electronics, calibration features, control loops, and error compensation methods in micro-machined angular rate sensors. In high volume production of angular rate sensors, the total basic price can be split into three parts[3]: manufacturing of the sensing element, the packaging including the readout electronics, and the test and calibration of the sensor. The desire to reduce cost and improve reliability has led to the development of improved calibration and testing techniques[4]. A simpler and more accurate procedure is desired to achieve higher productivity and thus reduce production costs, which opens the market for further applications.

This paper describes a prototype of a digital readout system with a procedure to determine the scale factor without a turntable. The improved electronics and the optimized software algorithm eliminate the need to adjust hardware parameters. The calibration method is also independent of the manufacturing tolerances. The results also show that the scale factor determination using the force due to gravity compares well with the determination using a turntable.

1 Operating Principle

Normally micro-machined angular rate sensors or gyroscopes consist of two rotary[5] or two linear[6]

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oscillation modes or some combination[7]. The principle of the micro-machined Coriolis vibratory gyroscopes (CVGs) is illustrated in Fig. 1 for a surfacemicro-machined structure with two linear degrees of freedom (DoF).

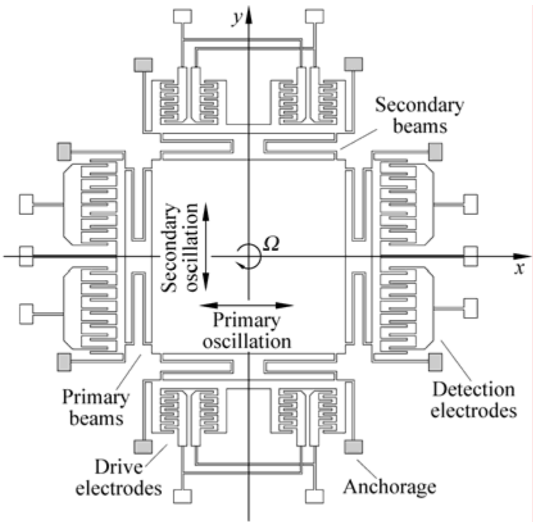


Fig. 1 Top view of the linear structure

The movable structure is electrostatically driven to linearly oscillate along the *x*-axis (called the primary oscillation) by drive electrodes (comb drives). When the device is turned (external angular rate) around its sensitive axis (*z*-axis), Coriolis forces arise which cause a linear oscillation along the *y*-axis (secondary oscillation). An advantage of this structure is that no substrate electrodes are required to detect the secondary oscillation as with other fabrication processes[8]. The amplitude of the secondary oscillation is directly proportional to the angular rate and is sensed by capacitance detection electrodes.

One major problem is to detect the capacitance changes caused by the Coriolis force or the force due to gravity during the initial calibration which are in the range of aF to fF[9]. An optimized adjusted amplitude modulation technique is used to detect these small changes, in a way similar to that used in micro-machined accelerometer readouts[10]. The imperfections and technology variations of the sensor manufacturing process, which result in geometric changes of the mechanical structures and different behaviors for each single sensor chip, are another key problem in sensor fabrication. These variations then require extensive testing, whereby each sensor is commonly mounted on a turntable to determine the ratio between the input angular rate and the sensor output signal, which is called the scale factor.

The sensor described here, built using low cost surface micro-machined technology with silicon on glass substrates and deep silicon etching, does not require turntable calibration, and can be simply calibrated using the gravitational force. A detailed scanning electron microscope (SEM) graph of the detection combs of a used micromachined angular rate sensor with two linear oscillation modes is shown in Fig. 2. The sensor works at ambient pressure with a thickness of about 80 μm and a high aspect ratio of about 25. The overall dimensions of the silicon chip are about 2.0 mm×2.2 mm and the resonant frequencies are in the range of 2-8 kHz for both the primary and secondary modes.

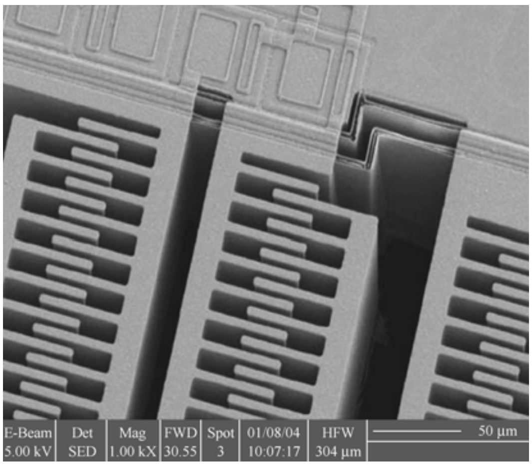


Fig. 2 SEM graph of linear micro-machined gyroscope

2 Calibration

The calibration method relates the Coriolis forces to the static force due to gravity as a reference. The Coriolis force, in the case of a primary resonance mode, can be expressed as

$$F_{\mathrm{cor}} = 2m_{\mathrm{iner}} v \Omega \tag{1}$$

where m_{iner} represents the inertial mass, v is the velocity of the primary oscillator, and Ω is the angular rate. The mass, m_{iner}, is related to the secondary resonant frequency, ω_{sec}, and the total stiffness of the secondary beams, k_{sec}.

$$m_{\mathrm{iner}} = \frac{k_{\mathrm{sec}}}{\omega_{\mathrm{sec}}^2} \tag{2}$$

The velocity, v, can be replaced by the amplitude, x, of the primary oscillation, the primary quality factor, Q_{prim}, the driving force, F_{drive}, and the total stiffness, k_{prim}, of the primary beams.

$$v = x\omega_{\text{prim}} = \frac{F_{\text{drive}}}{k_{\text{prim}}} Q_{\text{prim}} \omega_{\text{prim}} \quad (3)$$

Inserting Eq. (3) into Eq. (1) gives the Coriolis force as

$$F_{\text{cor}} = 2Q_{\text{prim}} \frac{\omega_{\text{prim}}}{\omega_{\text{sec}}^2} \frac{k_{\text{sec}}}{k_{\text{prim}}} F_{\text{drive}} \Omega \quad (4)$$

The driving force F_{drive} is then a function of the driving voltage U_{drive},

$$F_{\text{drive}} = C_x U_{\text{drive}}^2 \quad (5)$$

where the constant, C_x, is a function of the geometry of the primary drive electrodes. Using the known inertial value of the acceleration due to gravity, *g*, as a reference, the constant C_x and, thus, the driving force, by exception of the primary mass m_{prim}, can be expressed as measurable or calculated values.

However, the constant C_x is still sensor chip-specific, which means that the value differs for each chip because of the technology variations due to the manufacturing process.

$$C_x = \frac{U_{x\_\text{ac}} m_{\text{prim}} g}{Q_{\text{prim}} U_{x,1g} U_{\text{drive}}^2} \quad (6)$$

where U_{x_ac} represents the output voltage of the primary oscillation and $U_{x,1g}$ illustrates the voltage due to the gravitational force of the primary oscillator.

According to Eq. (5), the electrostatic force, F_{el}, to generate a secondary oscillation in absence of an external angular motion, can be written as

$$F_{\text{el}} = C_y U_{\text{sc}}^2 \quad (7)$$

The constant C_y can be determined in a similar way as for C_x in Eq. (6).

$$C_y = \frac{U_{\text{out}} m_{\text{iner}} g}{U_{\text{sc}}^2 U_{y,1g}} \quad (8)$$

where U_{sc} is the applied voltage at the secondary combs, $U_{y,1g}$ is the resulting voltage due to gravitational force of the secondary oscillator, and U_{out} is the output voltage proportional to the angular rate.

By equating the electrostatic force with the Coriolis force and assuming that the sensor will be driven at its primary resonance frequency, the recreated angular rate can be written as

$$\Omega_{\text{cl}} = \frac{(\omega_{\text{prim}} \pm \Delta\omega)(U_{x,1g} \pm \Delta u)(U_{\text{out}} \pm \Delta u)}{2(U_{y,1g} \pm \Delta u)(U_{x\_\text{ac}} \pm \Delta u)} \Delta\alpha \quad (9)$$

The computed scale factor, SF, can then be expressed as the ratio of measured voltages as

$$\text{SF} = \frac{U_{\text{out}} U_{\text{sta\_dc}}^2}{2U_{\text{ac}} U_{\text{dc}} \Omega_{\text{cl}}} \quad (10)$$

where $U_{\text{sta\_dc}}$ represents the DC voltage applied to the secondary combs, U_{ac} is the AC voltage with frequency ω_{prim}, and U_{dc} is the DC voltage applied together with U_{ac} to the secondary combs.

The force due to gravity *g* no longer appear in Eqs. (9) and (10) because it was canceled by equating Eqs. (5) and (7), so that the absolute value of the gravitational acceleration is not important.

All parameters in Eq. (10) are measured or calculated values that are chip-specific; therefore, the calibration is independent of the manufacturing tolerances.

3 Realization

A simplified block diagram of the prototype including the micro-machined structure and the digital readout electronics is shown in Fig. 3. All the applied or measured signals shown in the block diagram were realized within the digital readout electronics, so no additional equipment is needed. A calibration software algorithm was developed which runs according to the following sequence.

The first step determines the primary resonant frequency, ω_{prim}, using a frequency sweep, which will be used later to determine the frequency of the drive voltage, U_{drive}, and the resulting primary output voltage U_{x_ac}. Then the sensor is turned so that the primary and secondary oscillators are affected by gravity to read out the small signals $U_{x,1g}$ and $U_{y,1g}$.

In the third step, a DC-voltage $U_{\text{sta\_dc}}$ is applied to the secondary combs (U_{sc}) and the signal change, U_{y_dc}, is detected.

In the last step, the resulting output signal U_{out} is measured by applying a voltage $U_{\text{ac}} + U_{\text{dc}}$ with the drive frequency to the secondary combs.

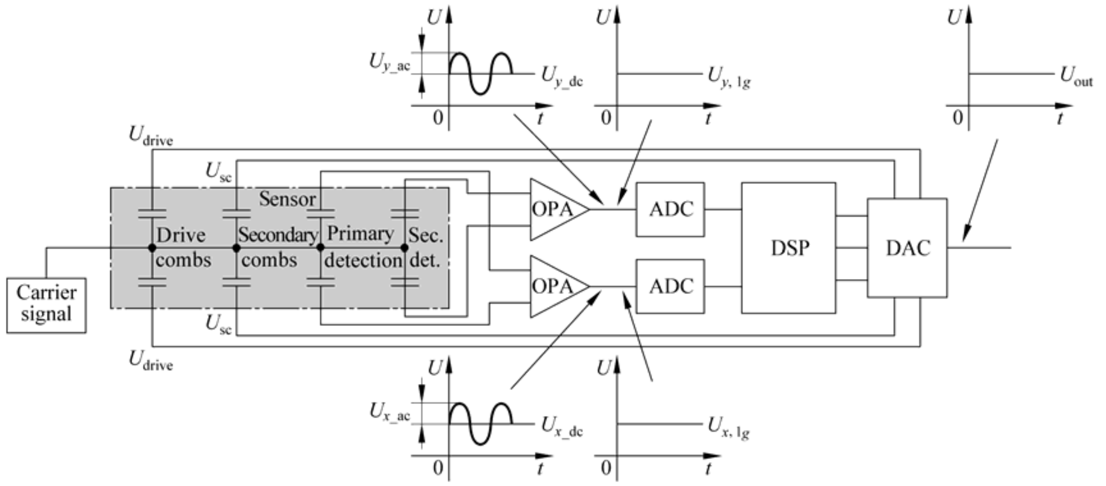
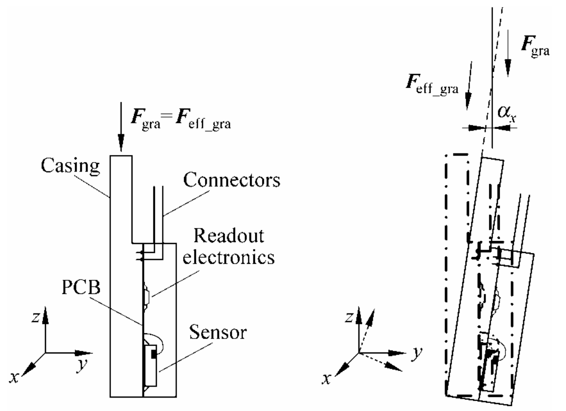


Fig. 3 Simplified block diagram of digital readout electronics (OPA stands for the operational amplifier, DSP the digital signal processor, ADC the AD converter, and DAC the DA converter)

Thus, all the parameters are measured and stored inside the digital signal processor (DSP). Equations (9) and (10) are then used to calculate the recreated angular rate, Ω_{cl}, and the scale factor, SF. The resulting value SF is then used to automatically adjust a gain factor inside the software.

Errors can occur due to inaccurate alignment and placement of the sensor die on the printed circuit board (PCB) with respect to the casing walls. Other error sources mainly come from the accuracy of the tipping angle (Fig. 4), the precision of the AD converter /DA converter, and the resolution of ω_{prim}.



(a) Ideal case (b) Tipping error α_x (1-dimensional)

Fig. 4 One main error source is the accuracy of the sensor relative to vertical, which affects the gyroscope

Applying Gaussian error propagation to Eq. (9), the error range is less than 0.2% assuming typical error values of $\Delta\alpha = \pm 2^\circ$, $\Delta u = \pm 2$ least significant bit (LSB) and $\Delta\omega = \pm 0.25\,\text{Hz}$.

The complete optimized digital electronics was realized using surface mounted device (SMD) technology on a printed circuit board with a good signal-to-noise ratio. Beside the initial calibration algorithm, the system also measures the angular rate with a digital phase-look-loop (PLL) to control the amplitude and phase of the primary oscillation. The digital miniaturized prototype including the micro-machined angular rate sensor (small casing) is shown in Fig. 5.

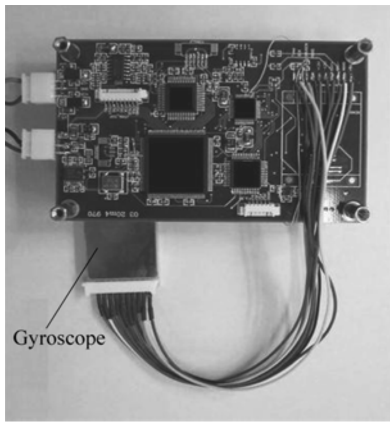


Fig. 5 Prototype of the digital readout electronics

4 Results

This calibration system was built to show the feasibility of measuring small capacitive changes caused by the acceleration due to gravity. The determination of scale factor with a turntable in the specified range of ±100°/s is shown in Fig. 6. The nonlinearity is less than

0.1% over the full measurement range using the end-point straight line method. The turntable scale factor (SF) is 18.81 mV/[(°) • s^{-1}] and the calibration scale factor is 18.98 mV/[(°) • s^{-1}]. The deviation between them is 0.95%. The deviation of about 1% shows that the method is accurate and thus suitable for a large range of applications.

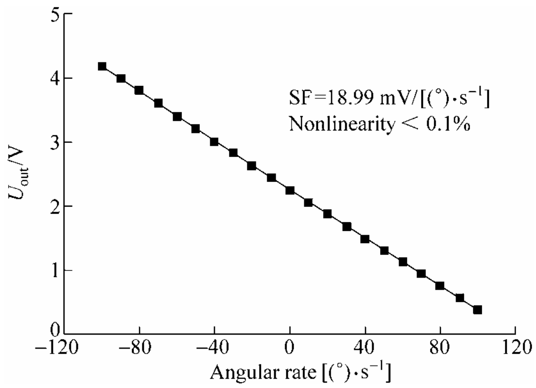


Fig. 6 Sensor output on a turntable

This angular rate sensor was then compared with other angular rate sensors from other suppliers producd using various manufacturing processes. The maximum deviation of the scale factor for these other sensors was 1.2% relative to the turntable measurements. Additionally, the digital prototype was quite insensitive to errors, such as the tipping angle relative to gravity or the inaccuracies of the generated frequencies.

5 Conclusions

A gyroscope was developed with a greatly simplified calibration system to determine the scale factor. The calibration results show that the accuracy meets the required specification, and that further reduction of the tipping error and increases in the resolution of the AD and DA converters will give even better results for the scale factor.

Common advantages of the calibration method in combination with the digital readout are:

- no expensive turntable is required;
- calibration is independent of technology variations;
- fast (not mounted on a turntable);
- standard silicon technology is used without any additional processing steps;
- highly accurate scale factor;
- common digital readout electronics can be used;
- force due to gravity is used instead of external angular rate.

This digital calibration method also provides the basis for future calibration features, like online self-diagnostics or online self-recalibration routines, to increase the reliability and performance of the angular rate sensors for new markets.

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