The signal detection for the levitated rotor micro gyroscope

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Abstract. In the novel prototype of micro gyroscope structure, the new configured capacitance sensing scheme for the micro gyroscope is analyzed and the virtual instrument based detection scheme is implemented. The digital lock-in amplifier is employed in the capacitance detection to restrain the noise interference. The capacitance analysis shows that 1000aF capacitance variation corresponds to 0.1 degree of the turn angle. The differential capacitance bridge and the charge integral amplifier are used as the front signal input interface. In the implementation of digital lock-in amplifier, a new routine which warranted the exactly matching of the reference phase to signal phase was proposed. The result of the experiment shows that digital lock-in amplifier can greatly eliminate the noise in the output signal. The linearity of the turn angle output is 2.3% and the minimum resolution of turn angle is 0.04 degree. The application of the digital lock-in amplifier in the field of micro-electro-mechanical-system (MEMS) device signal detection is a new attempt, and it shows the prospective for a high-performance application.

1. Introduction
The micro gyroscopes which based on the micro-electro-mechanical-system (MEMS) are the novel study fields for inertial sensors. In the past years, the research of the MEMS gyroscopes is mainly focused on the vibratory gyroscope, which is based on Coriolis Effect. However, the high micromachining accuracy and the complicated structure hampered the improvement of the gyroscope performance.

C.Shearwood and C.B. Williams described a new electromagnetically levitated structure for the application in the MEMS gyroscope [1][2][3]. Xiaosheng.Wu developed the levitation structure by using multi-coil and electromagnetic driving which has the advantage of large levitation force, good levitation stability and feasible micromachined process[6][7]. But the electromagnetic driving signal causes the much noise on the capacitance electrode, which in turn makes the implementation of signal detection circuit more difficult. The signal detection for the levitated micro gyroscope structure is seldom reported. Micheal Kraft and R Houlihan proposed a detection method used for a electrostatically levitated accelerometer [4][5]. The method is focused on the application in the electrostatic levitation environment. For the environment with electromagnetic noise, a new method to detect the weak capacitance submerged in noise is an urgent need. It is also a challenge to detect such a tiny capacitance variation about hundreds of aF(1aF=10^{-18}F).
2. Capacitance analysis and design of the detection scheme

2.1. Gyroscope structure

The structure of the electromagnetically levitated structure is shown in Fig.1 (a). The rotor is electromagnetically levitated upon the stator. The interval between rotor and stator forms the sensing capacitance, which is sensitive to the turn angle of the stator.

Fig.1 (b) shows the planar structure of the stator. The levitation and rotation coils are placed on the stator which provides levitation force and rotation torque. There are eight rotation coils provide the torque for the rotor to rotate around the center of stator. Four kinds of 2MHz sinusoid signals, which are different in phase for 90 degree respectively, are applied to the eight rotational coils.

The diameter of the rotor is 2.2 micro meter, the line width of the coils is 8μm. Four stability coils and levitation coils distributed around the outer circle of the stator. The inner levitation coils provide levitation forces, and the outer stability coils provide lateral stability. When the rotor slides off sideways, a force generated by the stability coils pushes the rotor to the center.

Currently, the rotor rotates at the speed up to 3000rpm. The conservation of momentum is the main effect of the rotor at this speed which keeps the rotor from turning its state. When the stator is turned, the output angle is proportional to the capacitance between the rotor and the electrodes.

2.2. The principle of angle detection

The capacitance electrodes are placed on the stator. Eight electrodes are configured as two pairs of differential capacitances to detect the turn angle of the stator. The capacitance between the sensing electrode and the adjacent coil is modified by the proximity of the rotor. The measured value of the differential capacitance is proportional to the turn angle, and ultimately to the angular rate of the stator. The relationship between input angle and the differential capacitance is calculated. As is shown in Fig.2, $\phi$ denotes the angle between surface normal and z axial, $\phi$ can be looked as the turn angle; $\alpha$ denotes the angle between the projection of the surface normal on the XY planar and the Z axial, $\alpha$ can
be looked as the direction of the turning. When $\alpha \neq 0$ and $\varphi \neq 0$, the function of the normal vector $\vec{l}$ can be expressed as following:

$$\vec{l} = (\sin \varphi \cos \alpha, \sin \varphi \sin \alpha, \cos \varphi)$$

(1)

On the condition of small turn angle, $\tan \varphi$ nearly equal to $\varphi$ and $\cos \varphi$ nearly equal to 1. The capacitance value can be derived as:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{z} = \varepsilon_0 \varepsilon_r \int_0^\varphi \int_0^\theta \frac{\rho}{h - \rho \varphi \cos \alpha \cos \theta + \rho \varphi \sin \alpha \sin \theta} \, d\rho \, d\theta$$

(2)

Where $\rho_0$ and $\rho_1$ denote the start and end radium of the capacitance electrode, $\theta_0$ and $\theta_1$ denote the start and end angle.

The result of the capacitance is calculated by Matlab. Four levitation heights are calculated to evaluate the linearity of differential capacitance. As shown in Fig.3, the curve of 50um levitation height shows the ideal linearity while 0.1° correspond to about 1000aF capacitance variation. The curve of 30μm levitation height does not have the linearity equivalent to 50 μm levitation height. And the curves of 70 μm and 100μm levitation height have relative low capacitance value.

Fig.2 The schematic computation of the capacitance structure

Fig.3 The relationship between turn angle and differential capacitance
The eight capacitance electrodes are configured as two pairs of differential capacitance which are sensitive to the two orthogonal directions on the horizontal plane. The rotor is looked as the middle electrode of the differential capacitance. For the detection of the angle in horizontal direction, the two sinusoidal excitation signals with anti-phase are applied to top electrode and bottom electrode. The output signal can be obtained on the common electrode. Limited by the unchangeable levitation structure of the stator and rotor, the signal is coupled by a capacitance $C_{1m}$ and $C_{2m}$.

2.3. Capacitance preamplifier

There are several methods to detect the value of capacitance. Such as the switched capacitance (SC), correlated double sampling (CDS), continued time current (CTC) and continued time voltage (CTV). In this work, the continued time voltage detection was used. Because the circuit was built on a printed circuit board (PCB), the SC and CDS require large amount of analog switches which would cause additional noise. In this work, the detection of the capacitance is implemented by the continue time capacitance bridge with sinusoidal excitation signal. A integral charge amplifier was used to be preamplifier. Fig.4 shows the schematic of one-channel structure of the front amplifier. The measurement of the angular position of the rotor in a capacitive sensing element is realized by applying a high-frequency sinusoidal signal to the capacitance electrode $C_{1t}$ and the same signal in anti-phase to the bottom electrode $C_{1b}$. $C_{1t}$ and $C_{1b}$ denote the top and bottom capacitance, while $C_{1m}$ is the couple capacitance formed by the capacitance structure. $C_p$ is the parasitical capacitance of the coaxial-cable and $C_f$ denotes the feedback capacitance of the integral charge amplifier.

![Fig.4 Preamplifier of continued time voltage detection circuit with double excitation](image)

To analyzing the circuit, the electric potential is equal on the both sides of the capacitance $C_p$, the effect of the parasitical capacitance $C_p$ can be neglected. This is the advantage to use the integral charge amplifier.

For the integral charge amplifier, a fast and precise low noise JFET-input operational amplifier AD795 is used. Because the system is linear and there are two sinusoidal signals applied into the circuit, the superposition method can be used to analyze the output signal.

The output is given by:

$$V_{out} = \frac{-C_{1t}(C_{1b} + C_{1m}) + C_{1b}(C_{1b} + C_{1m})}{(C_{1t} + C_{1b} + C_{1m})C_f} \times V_m$$

(3)

Equation (3) shows that the output voltage is proportional to the variation of $C_{1b}$ and $C_{1t}$.

3. Implementation and result

The implementation of the digital lock-in amplifier is under the Virtual Instrument environment. This is a prototype of the test, so a 12 bit 200 kHz sample rate analog to digital acquisition board and the LabVIEW software is used.
The hardware structure is shown in Fig.5. The angular signal is firstly detected by the capacitance bridge. The integral amplifier AD795 is used as preamplifier. The useful signal is only 3uV. In order to match the minimum level that the A/D converter can resolve, a signal conditioner procedure is applied to amplify the signal to the full scale of the A/D converter. The gain of the signal conditioner is 3200. The virtual instrument software is running in a personal computer which installed a 12-bit A/D acquisition board with 200 KHz sample rate.

The testing experiment was implemented by using a rotational platform which has the angular resolution of $1 \times 10^{-4}$ degree. The 10MHz sinusoidal signal was applied to levitate the rotor. To adjust the amplitude of the levitation signal, the levitation height was set to about 50um. A 10 KHz excitation signal was applied to the capacitance bridge. The experiment includes angle detection, angular rate detection and drift testing.

In the angle detection, the rotation platform moved from -2.5º to +2.4º, and the step is set to 0.1º. The relationship between turn angle and output voltage is shown in Fig.6 (a). The linearity calculated is 2.3%. The result shows that the prototype of the gyroscope is sensitive to the angle input. To reduce the angle step, the output voltage is still linear. The resolution of the angular displacement reaches 0.04º.

In the angular rate detection, five angular rates is applied to the platform, on the orthogonal of the input direction, the output angle is proportional to the input angular rate. The measured data is shown in Fig.6 (b).

Fig.6 The test result of the gyroscope
(a) turn angle versus output voltage; (b) angular rate versus output value;
The testing result shows that the circuit and software is sensitive to the turn angle and angular rate. The digital lock-in amplifier suppressed the noise effectively. The result is obtained under the 12-bit analog to digital converter, the curve of the angular rate to output voltage is not smooth. The reason is the interference of the environment and the noise on the PCB board.

4. Conclusion
The prototype of the gyroscope is introduced and the analysis of the capacitance is presented. The continue time voltage bridge is used in the capacitance detection. In order to suppress the noise caused by the electromagnetic interference, the digital lock-in amplifier which is realized by software is employed. A new method to ensure the exact match of the reference signal to capacitance signal is proposed. The result of the experiment shows that the noise was restrained effectively and the prototype gyroscope has the potential for high performance.

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