A TIA-based Readout Circuit with Temperature Compensation for MEMS Capacitive Gyroscope

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Abstract—This paper presents an integrated readout circuit based on trans-impedance amplifier (TIA) for MEMS capacitive gyroscope. The feedback resistors in TIA are realized in T-network pattern, which provides on-chip trans-impedance gains up to 22MΩ. A CMOS temperature-variable gain circuit is proposed to compensate the temperature induced sensitivity variance in MEMS and TIA. The demodulator, instrumental amplifier and low-pass filter for signal processing are also integrated on chip. In order to simulate the response of the circuit to the vibrating gyroscope, a gyroscope simulation model implemented in Verilog-A HDL is established, which can take the MEMS parameters influence into account. The circuits measure 0.8×1.7mm² in a standard 0.35μm CMOS process. The simulation results show that the TIA achieves a capacitive resolution of 0.42aF/√Hz at 2.5kHz with 75ppm/°C temperature coefficient from a single 5V supply.

Keywords- Capacitive readout; Gyroscope; Trans-impedance amplifier; Simulation model

I. INTRODUCTION

Low cost, high resolution MEMS gyroscopes with low drift rates are needed in a number of applications ranging from automotive to consumer products, aerospace to personal navigation systems. Most of MEMS gyroscope devices operate on the principle of detecting an induced Coriolis acceleration to the axis around which the input rotation is applied. Capacitive sensing is the dominant sensing mechanism in MEMS gyroscopes for its low power dissipation, low fabrication cost and high stability over other methods. In MEMS capacitive gyroscope, the rotation-induced capacitance change on sub-aF level always needs to be resolved by readout circuits, which poses a challenge to the low-noise readout circuits design.

Monolithic integration of the gyroscope device and readout IC is costly and rarely available for bulk micromachining processes. Thus, multi-chip packaging and wire bonding are often employed to interconnect sensor and IC dies. In such case, parasitic capacitances and leakage currents associated with the interconnection may incur sensing offset or errors that are comparable to or even larger than the useful signal. This paper presents a TIA-based low-noise readout circuits which is insensitive to these parasitic effects.

Temperature compensation is another critical issue for high resolution. Yet up till now few published works have implemented it in the front-end, but through complex digital logic. This paper presents a CMOS temperature-variable gain circuit following the TIA to compensate temperature drift, which demonstrates an excellent performances on both the resolution and temperature drift.

In this paper, Section II gives a brief introduction to the MEMS gyroscope system and the simulation model implemented in Verilog-A HDL for sensor and circuits co-simulation. Section III discusses the design of the low-noise TIA-based capacitive readout circuits in detail. Simulation results and conclusions are presented in Section IV and V.

II. CYROSCOPE AND SIMULATION MODELING

A bulk micromachined tuning fork gyroscope consists of proof masses, springs and combs structures[1], as shown in Fig.1. It works at atmospheric pressure with a resonance frequency around 2.5kHz. Capacitive sensing is used in the MEMS structure design to convert the angle rate input to the capacitance variance output.

In order to model the tuning fork gyroscope, a lumped behavioral model is established for MEMS and readout circuits co-simulation. Fig.2(a) gives a system-level representation of the coupling between drive mode and sense mode in tuning fork gyroscope. Driving force F_drive makes the proof masses resonating in X direction and brings a resonating displacement x(t). When the sensor undergoes a rotation about the z axis, a Coriolis force F_cor is generated in Y direction and brings a resonating displacement y(t) whose amplitude is in proportion to the input angle rate. The displacements x(t) and y(t) are finally converted into drive direction capacitive output C_d(s) and sense direction output C_s(t) in gyroscope, respectively.

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Figure 1. The MEMS gyroscope (a)SEM photograph (b)Structure diagram
Lumped behavioral model is shown in Fig.2(b), which is described by (1) to (4). The model includes two pairs of couple capacitors $C_{d,p/n}$ and $C_{s,p/n}$, representing the capacitive outputs of the drive and sense mode, and two input terminals $\Omega_z$ and $F_{drive}$ representing input angle rate and driving force.

\[ m_d \ddot{x}(t) + b_d \dot{x}(t) + k_d x(t) = F_{drive}(t) \]  
\[ F_{cor} = 2m \Omega_z \frac{dx(t)}{dt} \]  
\[ m_s \ddot{y}(t) + b_s \dot{y}(t) + k_s y(t) = F_{cor}(t) \]  
\[ C = \frac{N \cdot \varepsilon_0 \cdot A}{d} \]  

With $m$: proof mass, $b$: damping coefficient, $k$: linear spring constant, $N$: amount of fingers of comb, $A$: overlap area of fingers, $d$: air gap between fixed fingers and fingers of the moving mass. All these parameters are extracted from MEMS gyroscope in Fig.1.

The model is established using Verilog-A language, which is supported by most mainstream EDA tools and allows transforming mechanical quantities like angle, position and force into the electrical quantities voltage and current and therefore enables the modeling and simulation of electromechanical systems. Fig.3(a) shows the transient simulation output capacitance $C_{d,n}$ and $C_{s,n}$ from the previous model under a 10°/s 100Hz sinusoidal angle rate signal input. Fig.3(b) shows AC response in drive mode with quality factor of 100 and resonating frequency of 2.5kHz.

### III. CIRCUIT DESIGN

The readout circuits are shown in Fig.4. A low-noise fully differential trans-impedance amplifier first converts the change in sensor capacitance to voltage. A temperature-variable gain circuit further amplifies the Coriolis signal. The signal is then demodulated by a switch set type demodulator to give the rate and quadrature signal. An on-chip phase-locked loop (PLL) is adopted to generate resonance in drive mode and provide carefully phased signals (drv0° and drv90°) for signal demodulation. The rate signal from the two channels is then converted to single ended signal using an on-chip instrumentation amplifier and is low-pass filtered to yield an analog signal proportional to the rotation rate. Capacitors $C_{s,p}$ and $C_{s,n}$ represent the capacitive outputs of gyroscope sense mode which is proportional to the input angle rate. A DC polarization voltage $(V_p)$ of 12V is used to provide the bias for capacitive transduction and drive force. The previous gyroscope behavioral model is used both in readout and drive circuits simulation and design.

#### A. Fully differential trans-impedance amplifier (FDTIA)

In order to maximize the SNR of the readout circuit, a continuous time fully differential TIA readout scheme is adopted so that the noise performance is not degraded by the noise folding and the switch noise as existing in switch-capacitor circuits. TIA is widely used in optical receivers for sensing photocurrent from photodiodes. In capacitive sensors, the charge transfer generates an AC current which can also be sensed by the TIA\(^2\). The feedback resistor provides a good virtual ground at TIA input terminal and avoids the dc biasing circuits design at the sensing node, which is a major challenge in continuous-time voltage (CTV) sensing scheme.

![Fully differential trans-impedance amplifier and OTA with input common feedback](image)

Fig. 4. Block diagram of the TIA-based Readout Circuits
current from sensor capacitance change to voltage, which is difficult to realize on-chip. The strategy adopted in this work is to implement the feedback resistor using a T-network of resistors. Compared with method using the long MOSFETs biased in the linear regime in [3], T-network resistor will provide a broader output voltage range. The equivalent resistor \( R_f \) of T-network \( R_1-R_3 \) is given in (5), where the voltage divider formed by \( R_2 \) and \( R_3 \) in the feedback path provides an amplification of the equivalent trans-impedance.

\[
R_f = \frac{V_{\text{out}}}{I_{\text{in}}} = R_1 \left( \frac{R_2}{R_3} + 1 \right)
\]

Capacitance to voltage gain is as (6), which is relevant to resonant frequency \( \omega_0 \) and also shows a 90° phase shift. The C/V gain can be changed by altering resistor \( R_1 \) and \( R_3 \).

\[
\frac{V_{\text{out}}}{\Delta C} = (V_{\text{in,cm}} - V_p) \cdot R_f \cdot \omega_0
\]

The equivalent input noise capacitance for a TIA is given by (7) which includes the noise contribution of amplifier and feedback resistor \( R_f \).

\[
C_{\text{in,eq}} = \frac{4k_T}{T} \left( R_f + \frac{V^2_{\text{in,cm}}}{\omega_0^2} \right) \cdot \sqrt{B_W} \cdot \omega_0 (V_p - V_{\text{in,cm}})
\]

Where \( C_{\text{tot}} \) is the total parasitic capacitance seen at the input node, about 2–5pF, including pad capacitance in MEMS/ASIC and the input capacitance of amplifier, \( \omega_0 \) is the gyro resonating frequency, \( V^2_{\text{in,cm}} \) is input voltage noise of OTA, \( B_W \) is the bandwidth of gyros, \( V_{\text{in,cm}} \) is 2.5V bias voltage.

Furthermore to reject common-mode interference and match the differential capacitance input, fully differential topology is chosen in TIA. With the sensor element and TIA on separate chips, the level of leakage currents can be quite high, causing a voltage drop across the feedback resistors. If the output common-mode voltage is kept constant, the voltage over the sensor varies, thus changing signal gain. In this design, the problem was addressed by connecting the input of the continuous-time common-mode feedback (CMFB) circuit to the input of the operational amplifier, as shown in Fig. 5, instead of its output. Now, when the common mode voltage at the input tends to change due to leakage currents, the change is sensed and feedback, thus keeping the input \( C_{\text{tot}} \) voltage constant. A shunt capacitance \( C_f \) is placed in parallel with \( R_f \) for stability considerations and to alleviate gain peaking.

B. Temperature-compensation amplifier(TCA)

The temperature compensation is accomplished by adjusting the tail current of a resistively loaded amplifier over temperature, which forms an amplifier stage in the Coriolis channel, as shown in Fig.6. The stage gain is approximately 30 at room temperature. The tail current is created with a CTAT current generator[4], formed from transistors \( M_5-M_{13} \). These are fed with a complementary-to-absolute-temperature (CTAT) current \( I_{\text{CTAT}} \), and a constant current \( I_{\text{con}} \) both available from bias circuits. The tail current \( I_C \) changes with square of temperature shown in (8) and makes the gain of amplifier to vary linearly with temperature, which gives first-order temperature compensation to TIA and MEMS device sensitivity. All transistors in the current generator circuit have the same geometry.

\[
I_C = I_4 = \frac{1}{8 \cdot I_{\text{con}}} \cdot (I_{\text{CTAT}})^2
\]

C. Instrumental amplifier and low-pass filter

A three-opamp, two-stage instrument amplifier is adopted to further amplify the demodulated signal and provide differential to single-end conversion with high common-mode rejection, as shown in Fig. 7(a). The gain is programmable through tuning resistor \( R_G \). An integrated two-order low-pass filter uses off-chip capacitors \( C_1-C_2 \) to set the cut-off frequency to 100 Hz, whose low-pass gain can be trimmed by placing shunt resistor in parallel with \( R_8 \). The custom opamp of Fig.7(b), based on a topology in [5], is designed for the instrumental amplifier and the filter. \( M_3-M_8 \) provide class AB biasing to the output stage (\( M_1-M_2 \)).

IV. SIMULATION RESULTS

The readout circuit is designed and realized in a standard 0.35μm 2-poly/4-metal CMOS process of Chartered Semiconductor. The core of readout circuit measures \( 0.8 \times 1.7 \text{mm}^2 \) and operates with a single 5V supply. The layout is shown in Fig.8, with TIA-based readout circuit at the right part, which has recently been developed and taped out.
Fig. 9 plots the trans-impedance (I/V) and capacitance-to-voltage (C/V) gain and phase characteristics for TIA with $R_F=2M\Omega$. There is no gain peaking at the frequencies of interest by optimizing the ratio $R_2/R_3$ and adding shunt capacitance $C_F$. The C/V gain is about 0.3mV/fF at 2.5kHz which accords with the theory prediction from (6). The trans-impedance gain can be varied between 2M to 22M$\Omega$, i.e. about 0.3 to 3.3mV/fF C/V gain at 2.5kHz, by varying resistor array value of $R_3$. The C/V gain is about 0.3mV/fF at 2.5kHz which accords with the theory prediction from (6). The trans-impedance gain can be varied between 2M to 22M$\Omega$, i.e. about 0.3 to 3.3mV/fF C/V gain at 2.5kHz, by varying resistor array value of $R_3$. At the sensor operating frequency 2.5kHz, the maximum undesired phase deviation is found to be less than 1°, which is little enough for not adversely affecting the phase relationship among the sensor signals.

Fig. 10(a) plots the noise performance of the T-network TIA with $R_F=10.2M\Omega$ ($R_3/R_3=5$). The TIA shows an output noise down to 640nV/$\sqrt{Hz}$ at the gyro resonance frequency of 2.5kHz. The input-referred capacitive noise can thus be calculated as 0.42aF/$\sqrt{Hz}$. Fig. 10(b) shows that with increasing $R_F$, the capacitive noise floor decreases, as predicted by (7). Therefore, a larger $R_F$ leads to a lower noise floor and hence smaller minimum capacitance resolution. The deviation in noise performance between simulation and prediction, when $R_F$ is relatively small, comes from the noise gain by T-network of resistors.

Fig. 11. (a) TIA and TCA sensitivity vs. temperature. (b) Readout circuit sensitivity temperature drift.

Fig. 12. Readout circuit transient response to 10°/s 50Hz sinusoidal input angle rate with $R_F=2M\Omega$, IA gain=11, LPF gain= -10

The temperature compensation efficiency of the TIA readout circuit is verified in Fig.11. The TIA exhibits a positive temperature dependent sensitivity with about 550ppm/°C temperature coefficient (TC). Therefore, a negative temperature dependent gain is needed in TCA for compensation. By carefully tuning the current $I_{\text{PTAT}}$, we have obtained the optimum that the TIA and TCA overall readout sensitivity of 8.8mV/fF with temperature drift of 0.08mV/fF, i.e. merely 75ppm/°C TC.

Fig.12 shows the simulation output signal from the readout circuit when the previously described model is used to imitate the MEMS gyroscope with a constant rotation rate input with 10°/s amplitude and 50Hz frequency. The whole scale factor of MEMS system is about 5mV/(°/s) with $R_F=2M\Omega$, IA_gain=11 and LPF_gain= -10. The readout circuit exhibits an excellent signal integrity.

V. CONCLUSION

A low-noise fully differential TIA readout circuit for MEMS capacitive gyroscope is presented in this paper. The TIA is used as the core building block for both the drive and sense channels in the implemented sensor. Large trans-impedances are integrated on-chip by use of T-network of feedback resistors. Temperature compensation to suppress the temperature drift in readout sensitivity is accomplished by the proposed CMOS TCA. A Verilog-A gyroscope simulation model is also established for MEMS and circuits co-simulation. The TIA readout circuit is designed and implemented in standard 0.35μm CMOS process and shows a capacitive resolution of 0.42aF/$\sqrt{Hz}$ and 0.3 to 3.3mV/fF C/V gain with 75ppm/°C temperature coefficient. This low-noise readout
provides an attractive alternative to switched capacitor interfaces for MEMS gyroscope.

REFERENCES


