Modeling and Simulation of the Microgyroscope Driving Loop using SPICE

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Abstract. A simulation model of vibratory capacitive microgyroscope and its driving loop is designed using SPICE. The vibratory microgyroscope is basically microelectromechanical system; therefore the simulation model should be expressed mechanical and electrical properties. To modelling the microgyroscope, the Analog Behavioral Model is used. In order to design a driving loop of vibratory microgyroscope, the Barkhausen criteria is considered. The co-simulation of MEMS sensing element and its interface circuit is performed. The SPICE simulation model of the vibratory microgyroscope is designed, and the driving loop of the microgyroscope is simulated using the designed simulation model. The simulation results demonstrate the validity of the designed model and its interface circuit.

1. Introduction

A vibratory microgyroscope differs from most other micromechanical sensors in the complexity of its operation. The sensor does not give any output signal without mechanical excitation. In fact, this sensor is a true microelectromechanical system with equally important sensing, actuation and signal-processing functions. Moreover, for a capacitive micromachined gyroscope, the variance of the detection capacitance is in the range of attofarads, which requires high-resolution interfacing circuits. A simulation model combining the mechanical and electrical properties of microgyroscope should help in the design of such a critical device. The model also enables sensor simulation with interfacing electronics to analyze performances of the whole system and to optimize the design of testing circuits. An equivalent circuit representation has been successfully applied in electromechanical transducers [1] and micromechanical accelerometers [2]. The model of a vibrating gyroscope based on a dual torsional mass system has been implemented in the circuit simulation program APLAC [3].

This paper presents the simulation model for capacitive sensing vibratory microgyroscope and its simulation results with the designed driving loop using SPICE. The mechanical characteristics of microgyroscope is modeled using ABM (Analog Behavioral Model) and the driving loop is designed...
considering the Barkhausen criteria. To show the validity of proposed simulation model, the simulation is performed with the designed driving loop.

2. Working Principle of vibratory microgyroscope

The microgyroscope has two orthogonal resonant modes: driving mode and sensing mode. Figure 1 shows the schematic of the microgyroscope modeled in this paper. The outer and inner masses are driven together in the x-direction at the driving mode. If an angular rate is applied in the z-direction, then the inner mass moves in the y-direction by the Coriolis’ force. That is, the microgyroscope estimates the input angular rate by sensing the displacement of a proof mass induced by the Coriolis’ force.

![Figure 1. Schematic diagram of microgyroscope](image)

The dynamics of the microgyroscope can be modeled as two orthogonal mass-damper-spring systems as shown in Figure 2. The motion equations of plant dynamics are given by

\[
\begin{align*}
\text{Driving part:} & \quad (m_a + m_i)\ddot{x} + b_a \dot{x} + k_a x = F_e \\
\text{Sensing part:} & \quad m_s \dddot{y} + b_s \dot{y} + k_s y = F_e = 2m_s \Omega_s v_x
\end{align*}
\]

where \(m_a, b_a, k_a\) are mass, damping and spring coefficient of the driving part, \(m_s, b_s, k_s\) are mass, damping and spring coefficient of the sensing part, \(v_x\) is velocity of the mass which oscillates in sinusoidal motion by driving force, and \(\Omega_s\) is input angular rate. The transfer function of the vibratory microgyroscope is given by

\[
G(s) = \frac{Y(s)}{\Omega_s(s)} = \left[\frac{-v_a}{(j \omega_a + s)^2 + \frac{\omega_a}{Q} (j \omega_a + s) + \omega_a^2}\right] + \left[\frac{-v_a}{(j \omega_s - s)^2 + \frac{\omega_s}{Q} (j \omega_s - s) + \omega_s^2}\right]
\]

where \(\omega_a\) and \(\omega_s\) are the natural frequency of the driving and sensing mode, respectively. \(Q\) is the quality factor of the microgyroscope [4].
3. SPICE simulation modelling of microgyroscope

The modeling of microgyroscope is performed using a SPICE. Each of models is implemented as ABM (analog behavioral model). Mechanical interactions are communicated through node voltages in SPICE.

A mechanical mass-spring-damper is modeled by using ELaplace, VCVS (voltage controlled voltage source) type Laplace model. Table 1 is each mechanical parameter of the modeled microgyroscope. The SPICE model of microgyroscope is shown in Figure 3. When the two anti-phase same polarity driving sources are applied to actuation input ports, the input driving voltages are converted to driving forces. And then, the displacement change of actuation combs according to the applied forces is calculated at actuation body, which is modelled ELaplace model. Next, the calculated displacement change is converted to capacitance change using VCCAP (voltage-controlled-cap) implementation. In the VCCAP model, the output capacitance is multiplication of input voltage and reference capacitor. Thus the reference capacitor serves as the mechanical sensitivity of the combs for sensing driving motion. The parallel-connected capacitor between output nodes of VCCAP serves as nominal capacitance. To model the Coriolis’ force, the displacement of actuation part is differentiated and multiplied with $2m_j\Omega_z$. The modeling of the remaining sensing part is identical to the modeling of the actuation part.

Table 1. Mechanical parameter of microgyroscope

|                  | driving part | sensing part |
|------------------|--------------|--------------|
| Mass             | 1.07E-07 kg  | 5.76E-08 kg  |
| Stiffness of spring | 167.0 N/m    | 69.7 N/m     |
| Gap between combs | 2.3E-6 m     | 2.8E-6 m     |
| Overlap of combs  | 11.2E-6 m    | 199E-6 m     |
| Number of combs  | 2816         | 129          |
| Structure thickness |            | 40E-6 m      |
| Quality factor   |              | 1000         |
4. Design and Simulation of microgyroscope driving loop

The simulation of microgyroscope model and driving loop is performed using SPICE as the simulation program. Figure 4 shows the driving loop of the capacitive sensing vibratory microgyroscope.

In order to sustain the oscillation of driving loop, the driving loop should satisfy the Barkhausen criteria, a loop gain of larger than 1, phase lag of 180 degree. The capacitance changes due to the motion of the combs for driving sensing are detected by a charge-to-voltage converter. When the oscillation becomes steady-state, the phase lag is 90 degree in the microgyroscope actuation part. Therefore, the phase shifter with 90 degree phase lag is added to the driving loop. And then, the phase shifted signal is converted to driving source. The driving source is fed back to the actuation input ports. Figure 5 (a) shows the frequency response of the driving part, when ac signal applied to the microgyroscope. The phase lag is 90 degree at the oscillation frequency as shown in Figure 5 (a). Figure 5 (b) shows that the driving loop operates under the Barkhausen criteria and (c) is the simulation results of oscillation driving loop.
(a) Microgyroscope frequency response of the driving part

(b) Time domain output of driving loop
5. Conclusion
The co-simulation of MEMS sensing element and its interface circuit is performed. The SPICE simulation model of the vibratory microgyroscope is designed, and the driving loop of the microgyroscope is simulated using the designed simulation model. The mechanical operation of the microgyroscope is modelled using SPICE ABM, which provides the more complex implementation than the conventional lumped parameter model. The simulation results demonstrate the validity of the designed model and its interface circuit.

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