Mechanical Systems and Signal Processing 70-71 (2016) 1209–1220

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

An improved interface and noise analysis of a turning fork microgyroscope structure

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ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form
24 June 2015
Accepted 3 August 2015
Available online 11 September 2015

Keywords:
MEMS gyroscope
Structure noise
Carrier frequency
Temperature
Quadrature error compensation

ABSTRACT

This paper analyzes different noise components in MEMS gyroscope silicon structure, including mechanical–thermal noise (MTN), electronic-thermal noise (ETN), flicker noise (FN) and Coriolis signal in-phase noise (IPN). The structure equivalent electronic model is established, and the improved differential interface is proposed based on weak signal detection technology, after that, the noise components in silicon structure are introduced and analyzed in sense open loop. The quadrature error (QE) signal automatically cancellation loop is proposed, and the results of the experiment indicate that the equivalent angular rates of QE and IPN are 46°/s and 4.55°/s respectively. The interfaces contrast experiments show that the DC noise and the useful signal amplitudes of differential and single-side detection interfaces are −49.8 dBmV, −16.8 dBmV and −39.8 dBmV (−42.1 dBmV), −22.1 dBmV (−22.2 dBmV), which confirms the differential interface has better SNR. The carrier experiments also illustrate that higher carrier frequency (from 500 kHz to 10 MHz) can restrain DC noise (from −19.8 dBmV to −54.2 dBmV) better, which demonstrate the FN is the dominant noise component of the silicon structure under normal temperature. The temperature experiments show the DC noise enhances from −48.5 dBmV to −14.6 dBmV over the range 20 °C to 60°C while the useful signal amplitude remains around -16.6dBmV, and this phenomenon indicates the MTN and ETN become the dominant structure noise components gradually with temperature rising.

1. Introduction

With the development of the manufacture process and monitoring technology, the accuracy of the MEMS inertial devices (gyroscope and accelerometer) improves a lot during this decade. Their precision can satisfy more and more application areas [1–3], such as automobile safety, MIMU navigation system, consumer electronics and so on. The noise becomes another obvious

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http://dx.doi.org/10.1016/j.ymssp.2015.08.002
0888-3270/

bottleneck that limits the MEMS devices performance [4,5], and many previous literatures dedicate great efforts to restrain MEMS devices noise. The researches in [6–8] indicate that the noise source of capacitive measurement based MEMS structure mainly contains the mechanical noise which is generated from the mechanical vibration of the polysilicon springs, the measurement system noise and the circuit electrical noise. And the electrical noise is larger than the mechanical noise, the electrical noise can be decomposed as thermal noise, shot noise, FN ($1/f$ noise), kT/C noise and quantization noise, meanwhile, the experiments show that the $1/f$ noise and the white Gaussian noise govern the low and high frequencies domain respectively. The work in [9] claims that ETN and FN are the dominate noises in bulk micro machined devices, and a novel interface with low flicker noise is proposed. Based on a new ideal gyroscope model, the work in [10] investigates MTN with its power spectral density and equivalent rate in both sense-open and sense-close loop, and more work focuses on the MTN influence on angle random walk. The results present that the MTN equivalent rate as well as the angular random walk in open loop is smaller than that in close loop. Particular research has been implemented in [11], whose conclusion indicates that the MTN is a major noise source in MEMS gyroscope, and high quality factor is beneficial to decreasing the MTN. Meanwhile, the wider bandwidth brings larger noise equivalent angular velocity. Several techniques for calculating the MTN are discussed in [12], and it is reported that the magnitude of MTN only depends on temperature and mechanical damping magnitude, and the MTN can be considered as a force generator alongside each damper when the mechanical system in thermal equilibrium state. The influence from both MTN and electronic noise (ELEN) are investigated in [13], and an improved performance data-acquisition system is employed to quantitate the noise of power supply, MEMS device structure, front-end electronics, timer and $1/f$ noise. Furthermore, it is also proposed that $1/f$ noise is involved with the roughness of the moving surface, and the results are found to be reproducible in the same devise manufacture process. The work in [14] investigates $1/f$ noise component in MEMS gyroscope bias with a $1/f$ noise model, and utilizes a Kalman predictor together with a moving average predictor to predict the bias. The MTN and ELEN are analyzed in [15] based on MEMS gyroscope open loop and close loop, the rate-equivalent noise (REN) achieves the minimum value when the gyroscope is tuned (mode match), and REN increases with drive and sense modes resonant frequencies split value. The noises in sigma-delta modulator circuit are investigated in [16] and [17], which includes Brownian noise, thermal noise, kT/C noise and quantization noise (comes from the AD device), sensor charge referencing voltage noise and quantization noise, and the experiment shows that noise components play different roles in different circuit working conditions.

This paper proposes a novel equivalent electrical model of the silicon structure, and according to this model, the different noise components are investigated. After that, a classical weak signal detection method is employed in gyroscope interface to restrain the noises in gyroscope's structure. The noises are modeled and analyzed in sense open-loop condition, and the experiments are arranged to observe the noise amplitudes and components.

2. Gyroscope model

The MEMS gyroscope ideal model includes two parts: drive mode and sense mode, and each mode can be described as a spring-mass-damping second order system. A decoupled structure is employed to eliminate the quadrature error which is caused by manufacture imperfect, and the structure equivalent model is shown in Fig. 1.

It can be learned from above figure that the drive mode has one DOF along x direction and includes drive frame, drive stiffness k_x and drive damping c_x; sense mode contains sense frame, sense stiffness k_y and sense damping c_y, and has one DOF in y axis; Coriolis mass m_p has two DOF in both x and y axis. After neglecting the coupling stiffness, damping and small force components, the ideal dynamics of this structure can be governed by [2] [18]:

$$\begin{cases} m_x\ddot{x}+c_x\dot{x}+k_x x=F_d\ \sin(\omega_d t) \\ m_y\ddot{y}+c_y\dot{y}+k_y y=-2m_p\Omega_z\dot{x} \end{cases} \tag{1}$$

where m_x, m_y are the equivalent masses of drive and sense modes, x and y are the displacement of drive and sense frames, F_d is drive force amplitude and ω_d is drive force angular frequency, Ω_z is angular rate around z axis. Then define:$\omega_x=\sqrt{k_x/m_x}$,

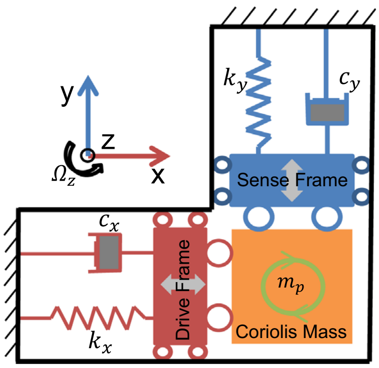

Fig. 1. Mechanical model of gyro's structure.