Design and performance analysis of a nanogyroscope based on electrostatic actuation and capacitive sensing

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A B S T R A C T
In this paper, a vibrating beam gyroscope with high operational frequencies at mode-matched condition is proposed. The model comprises a micro-cantilever with attached tip mass operating in the flexural-flexural mode. The drive mode is actuated via the electrostatic force, and due to the angular rotation of the base about the longitudinal axis. The secondary sub-nanometric vibration is induced in the sense direction which causes a capacitive change in the sense electrodes. The coupled electro-mechanical equation of motion is derived using the extended Hamilton's principle, and it is solved by direct numerical integration method. The gyroscope performance is investigated through the simulation results, where the device dynamic response, rate sensitivity, resolution, bandwidth, dynamic range, g sensitivity and shock resistance are studied. The obtained results show that the proposed device may have better performance compared to commercial micro electromechanical gyroscope characteristics.

1. Introduction

Gyroscopes as angular rate sensors find broad range of applications from automotive to aerospace and consumer electronics industries. Optical and mechanical gyroscopes in comparison with micro-machined vibratory gyroscopes are more accurate and have better scale factor stability [1]. However, they are too expensive and too bulky. The micro-machined gyroscopes due to their small size, light weight, low power consumption and low cost find application in automotive and electronic consumer and makes them ideal for use in handheld applications. Today, common silicon micro-machined vibratory gyroscopes operate in low frequency range (3–30 kHz) which suffer from the low bandwidth and bias stability and low reliability due to low shock resistance [2]. To increase the scale factor, resolution, and bias stability a high quality factor is desirable which is accomplished by device packaging in high vacuum. It may be further noted that, even in high vacuum, the effective quality factor is restricted by thermoelastic damping [3,4]. In some applications such as automotive, a very fast response time is required. Consequently, higher bandwidth is desired which could be achieved by increasing the resonant frequency or decreasing the quality factor of the gyroscopes. Although, the later, decreases the scale factor, and the performance of the device.

Micro/nano cantilevers have finded various applications such as mass sensor [5,6], resonators [7], atomic force microscopes [8] and vibrating beam gyroscopes. Electrostatic actuation as a versatile and applicable method is employed to design and develop various micro/nano electromechanical systems (MEMS/NEMS) [9–13].

Recently vibrating beam gyroscopes as an interesting issue has obtained more attention. The optimal size and the level of thermal noise of a vibrating beam gyroscope have been investigated and it is shown the longer the beam the lower the
thermal noise [14]. Rotating beams with piezoelectric films as an angular rate sensor has been investigated [15].

The finite element modeling of a rotational motion sensor which uses tuning fork to sense the angular rate has been performed and dynamic properties of the sensor have been investigated [16]. Dynamic characteristics of a gyroscope based on beam element modeling of a rotational motion sensor which uses tuning fork to sense the angular rate has been performed and thermal noise [14].

Several companies provide microgyroscopes as standard components. The first of these was an integrated gyroscope announced in 2002 by Analog Devices Inc. (ADI), offering a very high resolution of 0.05 °/s/√Hz [23]. Robert Bosch presented a z-axis gyroscope with 1.5 °/s/√Hz resolution and 30 Hz frequency bandwidth [24]. In 2006, a high resolution gyroscope (SiRRS01) was introduced by Silicon Sensing, with noise density of 0.35 °/s/√Hz and 50 Hz bandwidth [24].

Northrop Grumman Corporation introduced a MAG-16 MEMS gyroscope with 0.03 °/s/√Hz resolution and operational range of 150 °/s [25]. Later on, in 2007, InvenSense Inc. offered the first commercialized dual-axis integrated gyroscope (IDG-300). Its resolution was claimed of 0.014 °/s/√Hz in operational range of 50 °/s [26].
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