A Tri-Axial Angular Accelerometer for Vestibular Prostheses

Yu Kitamura
Graduate School of Engineering, Kobe University, Japan

NNIN iREG Site: Institute for Electronics & Nanotechnology, Georgia Institute of Technology, Atlanta, GA

NNIN iREG Principal Investigators and Mentors: Professor Farrokh Ayazi and Professor Pamela T. Bhatti, School of Electrical and Computer Engineering, Georgia Institute of Technology

Contact: 131t328t@atu.kobe-u.ac.jp, ayazi@gatech.edu, pamela.bhatti@ece.gatech.edu

Introduction:

The vestibular system is the system that informs the brain about head motion and orientation to keep stabilization of the visual axis, head and body posture. Because vestibular disorders are common and often cannot be treated by existing approaches, vestibular prostheses had been investigated [1]. A vestibular prosthesis captures angular and linear head motion using inertial sensors. This information is coded as current pulse waveforms and applied to vestibular nerves. As a result, the prosthesis provides the central vestibular system with information about head motion and orientation. For an implantable vestibular prosthesis, it is paramount to reduce system power as well as size. Especially, gyroscopic sensors, which detect angular acceleration, are key components of vestibular prostheses systems [2]. Their performance determines the performance of the whole system in terms of power consumption.

There are mainly two methods to detect angular acceleration, direct measurement and indirect measurement. Recently, gyroscopes that utilize the indirect measurement method are widely used for motion detection because of their high sensitivity. Current gyros are based on the Coriolis effect, which requires a vibratory structure in order to achieve the required sensitivity. Due to input vibratory signal, however, they consume high power. On the other hand, power consumption of angular accelerometers, which use the direct measurement method, is lower than gyroscopes, because they have a passive sensor that does not require vibratory input signal.

This summer, we focused on developing a tri-axial angular accelerometer for vestibular prostheses to take advantage of the low power consumption of angular acceleration sensors in order to reduce battery size and extend battery life of the prosthesis device.

Table 1 summarizes the requirements angular accelerometers have to fulfill for the application of a vestibular prosthesis. The maximum detectable signal is required to be larger than 1000 r/s^2. This is the maximum value evaluated by 700 test samples in daily activities [3]. The minimum detectable signal is required to be smaller than 1.75×10^{-2} r/s^2, which is the same value of resolution of human vestibular systems evaluated by the deviation of the eye caused by vestibule-ocular reflex [4]. Finally, the bandwidth is required to be approximately 20 Hz.

Device Design:

To detect three axis angular acceleration, we proposed two types of devices, showed in Figure 1(a). Both of these sensors are capacitive sensors designed on a silicon-on-insulator (SOI) substrate. The Z axis sensor, called a yaw angular accelerometer, has one proof mass suspended to the anchor that is placed at

Parameter	Requirements	Device characteristics
Maximum detectable signal	1000 [r/s^2]	Linear operation range > ±1000 [r/s^2]
Minimum detectable signal	1.75E-2 [r/s^2]	TNEA<1.75E-2 [r/s^2] $\mathrm{TNEA} = \sqrt{BNEA^2 + CNEA^2}$
Bandwidth	20 [Hz]	

TNEA: Total Noise Equivalent Acceleration
BNEA: Brownian Noise Equivalent Acceleration
CNEA: Circuit Noise Equivalent Acceleration

Table 1: Specification requirements of angular accelerometer for vestibular prostheses.

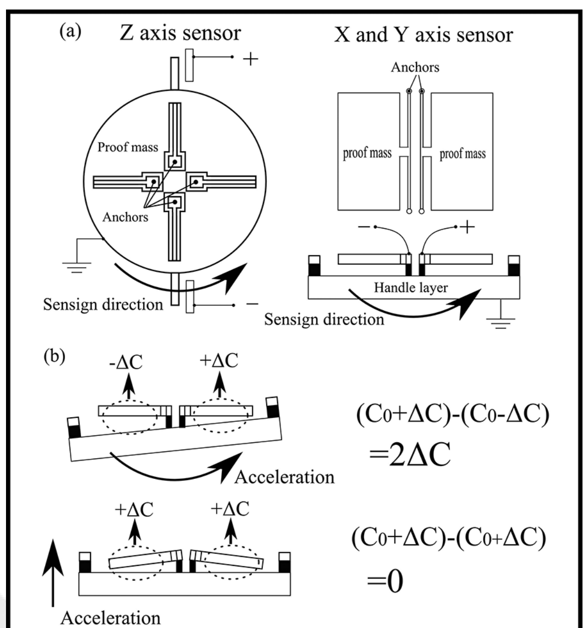

Figure 1: Schematic diagram of (a) angular accelerometers and (b) detection principle of differential design.

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the center of the device by four beams. X and Y axis sensors, called roll and pitch angular accelerometers, have two proof masses that are connected to dual anchors by a torsion beam. We employed an in-plane gap of device layer to detect Z axis angular acceleration, and vertical gap between device layer and handle layer to detect X and Y axis angular acceleration. Thanks to utilizing a handle layer as bottom electrodes, these devices can be fabricated with one mask process.

In order to reduce cross axis sensitivities, we employed a differential capacitor design as showed in Figure 1(b). These devices were designed to generate capacitance change only by demanded direction of angular acceleration. In Figure 1(b), when demanded angular acceleration is applied to the device, capacitance change, detected by the differential circuit, will be generated. On the other hand, when other direction acceleration is applied to the device, for example linear acceleration, differential capacitance change will not be generated. As a result, cross axis sensitivities decrease.

Simulation Procedure:

At first, we designed each device within 1 mm × 1 mm size and optimized to achieve high sensitivity. Although large proof mass and narrow beams are preferred to get high sensitivity, there was a concern about stiction, which happens during fabrication process. To avoid this problem, we defined the device layer thickness as 40 μm and the gap distance between electrodes as 2 μm. Also we employed a beam width of 5 μm —the minimum value at which we could fabricate a 40 μm thick device layer with width:height = 1:10 aspect ratio. Then, we swept each device size and compared device specifications, such as sensitivity and maximum detectable signal.

Results and Conclusions:

Figure 2 shows the simulation results of the linear operation limit and sensitivity versus device size for the Z axis sensor, and the X and Y axis sensor. In Figure 2(a), fulfilling the requirement of the maximum detectable signal (> 1000 r/s^2), demanded that the device diameter of the Z axis sensor be smaller than 2.6 mm. In Figure 2(c), fulfilling the requirement of sensitivity calculated from the minimum detectable signal requirement, demanded that the device diameter be larger than 2.1 mm. In the same procedure, we concluded that the X and Y axis sensor's side length must be larger than 1.7 mm and smaller than 1.9 mm to fulfill both requirements. Finally, we defined the device diameter of the Z axis sensor as 2.1 mm and the device side length of X and Y axis sensor as 1.7 mm, which are the minimum values to fulfill both requirements.

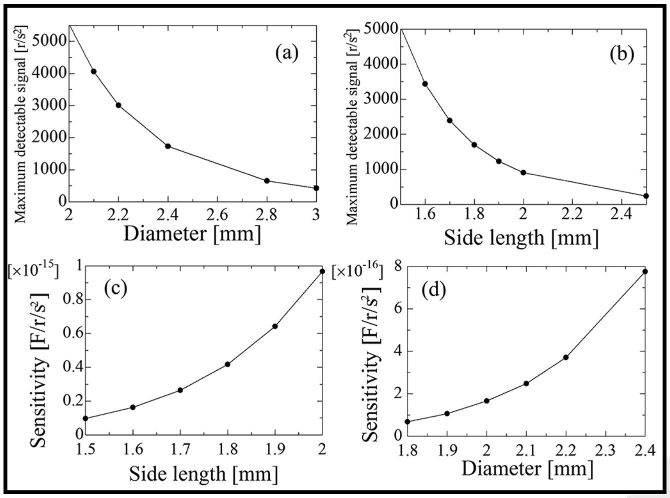

Figure 2: Simulation results of Z axis sensor's (a) maximum detectable signal and (c) sensitivity versus device diameter, X and Y axis sensor's (b) maximum detectable signal and (d) sensitivity versus device size.

Table 2 shows detailed device specifications calculated by a COMSOL simulation. These specifications fulfilled requirements for the application of vestibular prosthesis.

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	Z axis sensor	X and Y axis sensor	Requirements
Device size	2.1mm × 2.1mm	1.7mm × 1.7mm	
Sensitivity [aF/rad/s^2]	248	267	200
Minimum detectable signal [rad/s^2]	1.21×10^{-2}	1.13×10^{-2}	$< 1.75 \times 10^{-2}$
Maximum detectable signal [rad/s^2]	4059	2391	>1000
Bandwidth [Hz]	500	300	>20
Cross axis sensitivity (angular)			
Z [%]	-	<<0.1	<0.1~1
X , Y [%]	<<0.1	<<0.1	<0.1~1
Cross axis sensitivity (Linear)			
Z [%]	0.01	0	<0.1~1
X [%]	0.025	<<0.1	<0.1~1
Y [%]	0.025	0.05	<0.1~1

Table 2: Detail specifications of angular accelerometers.