Modelling, Design, and Fabrication of A Bio-inspired MEMS Vibratory Gyroscope

Y. Chen, D. H. B. Wicaksono, L. Pakula, V. Rajaraman and P. J. French

Abstract— **Micromachined gyroscopes for measuring rate or angle of rotation have attracted a lot of attention during the past few years for several applications. They are widely used to detect orientation in space [1], including automotive applications for ride stabilization and rollover detection; some consumer electronic applications, such as video-camera stabilization, virtual reality, and inertial mouse for computers; robotics applications; and a wide range of military applications. This paper is our report of an on-going work to develop a new MEMS-based vibratory gyroscope which is inspired by a natural "gyroscope", i.e. the halteres of insects. Halteres are small evolutionarily modified hind wings of insects, which beat anti-phase to the wings and serve a purely sensory function during flight. The halteres are very sensitive to Coriolis forces and potentially provide an accurate measure of angular velocity which originate from angular rotations of the body and mediate corrective reflexes during flight. In this paper, the authors present the preliminary design of the new bio-inspired MEMS-based vibratory gyroscope. The initial Finite Element (FE) simulation results based on our preliminary design of a new generation Surface-micromachined MEMS vibratory gyroscope are also presented and discussed. The fabrication process and experiment for the initial design are illustrated. Fabrication is presently underway..**

Keywords—Bio-inspired, Gyroscope, MEMS

I. INTRODUCTION

During the past few years, microelectromechanical systems (MEMS) gyroscopes for measuring rate or angle of rotation have attracted a lot of attention for several applications [1]. They can be used either as a low-cost miniature companion with micromachined accelerometers to provide heading information for inertial navigation purposes or in other areas which includes: intelligent cruise control (automotive), rollover detection (automotive), control of vehicle dynamics (automotive), crash sensors (automotive), flight control and test instruments (commercial), cockpit display stabilization in aircrafts (commercial), platform stabilization (industrial). Among many MEMS gyroscopes, Coriolis vibratory rate gyroscopes have demonstrated a significant progress within the past decade satisfying the requirements of several applications such as guidance, robotics, tactical-grade navigation, and automotive applications [1]. There has been a great deal of research on Coriolis vibratory gyroscopes [2-6], which has indicated that the Coriolis vibratory gyroscopes have many potential advantages: they can be mass produced and can have both driving and detecting circuits integrated on-chip for improved sensitivity, and the whole gyroscope system can be very small and inexpensive.

Although certain precise MEMS vibratory gyroscopes are commercially available, basically due to the designs, such as package size, power requirements, etc., their applications in micromechanical robotics are still limited. The authors believe that the capabilities of the MEMS vibratory gyroscope could further be enhanced by learning the gyroscopes found in nature.

Halteres, also known as balancers or poisers, are small knobbed structures found as a pair in some two-winged insects (*Diptera*). In order to maintain stability while flying, they are flapped rapidly to detect body rotational velocities by measuring Coriolis forces [7, 8]. Research on biology has demonstrated that fly's haltere system is playing an indispensable role for its impressive maneuverable and elaborate flight behaviors [7, 9].

However, the real fly's gyroscope is very complicated and includes several organs to detect the Coriolis force, i.e. vibrating halteres, strain receptor fields (*campaniform sensilla*), and visual control system [9]. Each organ has its unique structure, functions and consists of different materials with different mechanical properties. Therefore, the implementation of the new MEMS vibratory gyroscope in silicon structure will be carried out in stages [10]. In order to move closer to the natural gyroscope system [7], the structure will then be improved gradually by adding other structural features of the real fly's gyroscope, such as the biomimetic strain sensor inspired from *campaniform sensilla* [11].

In this paper, the preliminary design and initial simulation results will be used to investigate the mechanical properties of the preliminary structure of our designed bio-inspired gyroscope. The fabrication process for our initial design will

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be also introduced.

II. GYROSCOPES IN NATURE

The halteres of an insect, e.g. *Musca domestica* (house fly), are located in its hindwings, and are hidden in the space between thorax and abdomen where the air current has a negligible effect on them (see Fig. 1) [12]. The measurements dimensions of the left haltere of *Drosophila* [13] are illustrated in Fig. 2. Each haltere contains approximately 400 mechano-receptors [11] (Fig. 2), mainly *campaniform sensilla* and chordotonal organs, embedded in the flexible exoskeleton at the haltere base. Derham [14] was the first scientist to note that when their halteres are removed, flies cannot keep stability and quickly crash to the ground while staying aloft. In reality, those mechanoreceptors at the base of the halteres function as strain gauges to detect the Coriolis force applied on the halteres [7].

Fig. 1. The arrow is pointing on the right haltere of *Musca domestica* (house fly). Courtesy of CSIRO Entomology [12].

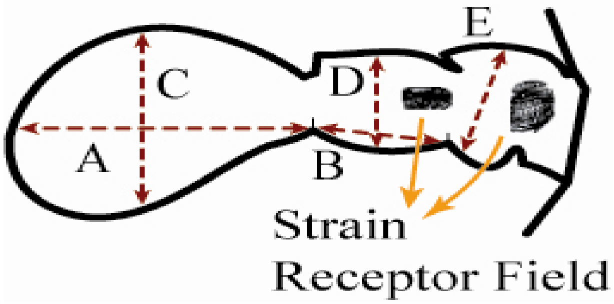

Fig. 2. Outline of left haltere of *Drosophila*, dorsal aspect, anterior side at top, and the mechano-receptors at its root, i.e. campaniform sensilla. The measurements of dimensions: A~180 µm, B~75 µm, C ~115 µm, D ~61 µm, E ~79 µm. Modified from [8] and [13]

As illustrated in Fig. 3, during flight the halteres beat up and down in vertical planes through an average angle of nearly 180° anti-phase to the wings at the wing beat frequency, which is approximately 200 Hz for housefly [15, 16]. In addition, the two halteres are non-coplanar (each is tilted backward from the transverse plane by about 30°) so that flies can detect rotations about all three turning axes [15, 17]. In fact, a fly with one haltere removed is unable to detect rotations about an axis perpendicular to the stroke plane of the remaining haltere [15]. Mathematical investigations and numerical simulations of the signal processing of the halteres presented in [18], confirm the idea that insects can indeed estimate the three components of the angular velocity.

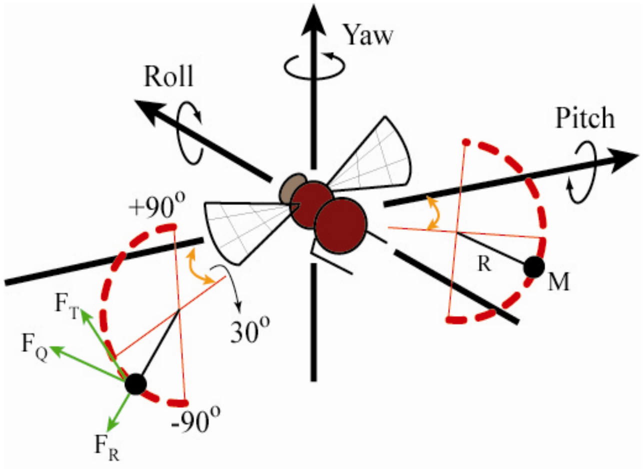

Fig. 3. The coordination system of the fly with schematic representation of the halteres configuration. F_T: the tangential force, F_Q: the lateral force, F_R: the radial force. Modified from [15]

III. STRUCTURE DESIGN

Large sensitivity, low noise, selective mode matching and separation, undesired vibration coupling, and external translational acceleration rejection must be carefully considered during gyroscope design. Of prime importance is that the gyroscope designer must consider the structural imperfections due to material behavior and process variations, which affect these performance metrics. Large proof mass, desirable for high sensitivity, is hard to realize in surface micromachining processes, but relatively easy in bulk micromachining processes. Structural thickness is limited to around 10 µm for uniform thin-film deposition and structural area is limited to around 1 mm on a side to avoid problems with out-of-plane structural curling and with sticking to the substrate. However, the surface micromachining fabrication processes is much more straightforward than bulk micromachining processes. Large amount production of devices in single chip is also a distinguished advantage for surface micromachining processes. Therefore, surface-micromachined gyroscope will be considered for our preliminary design.

The capacitive sense interface circuit design is also a very challenging problem for both surface- and bulk-micromachined gyroscopes. Surface-micromachined gyroscopes have a typical sense capacitance of 0.1 pF. Bulk-micromachined gyroscopes normally have a relatively larger sense capacitance of 1 pF or greater, but most bulk silicon gyroscopes have not been integrated with electronics, moreover the parasitic capacitance introduced by the wire bonding to electronic chips can greatly attenuate the signal. The lack of integrated bulk silicon gyroscopes is partly due to the incompatibility of wet silicon through-wafer etching and wafer bonding with foundry electronics processes. Consequently, the piezoresistive sensing method will be used in this bio-inspired gyroscope. Based on previous work [10], the first and easiest stage of design will be silicon structure with least similarity to the original haltere structure, still with pillar rotary movement to detect the Coriolis force. The preliminary design of the bio-inspired surface-micromachined gyroscope is illustrated in Fig. 4.

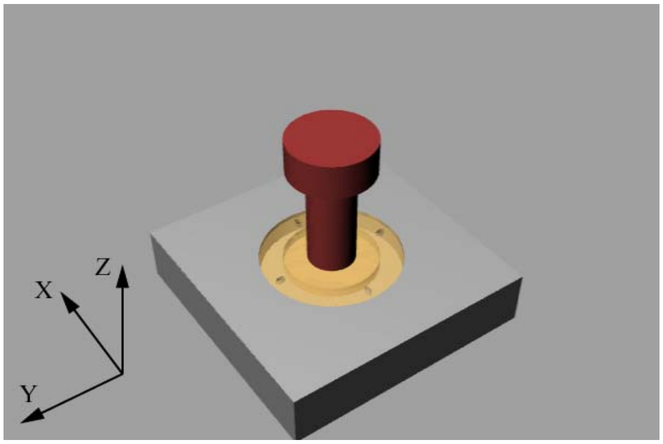

Fig.4. Surface-micromachined Bio-inspired gyroscope with a standing pillar and suspending membrane

The mass in Fig. 4 is a thick layer of membrane which is suspended by a thin layer of membrane. The piezoresistors are based on the bio-mimetic strain sensing microstructures [19], which are shown as the elliptical holes in Fig. 4. As illustrated in Fig. 5, the whole structure can be driven with a swinging model in x-axis by an electrostatic force that is generated by a driving voltage across the electrodes underneath the thick layer of the membrane. The Coriolis acceleration arising from an angular rate around the z-axis causes the moving structure to vibrate in the sensing. The standing hammer-shape structure on the thick layer of membrane is to imitate the structure of the halteres of insects, which will offer extra momentum amplification towards the Coriolis force input. Compared with the conventional suspension beams, the suspension thin layer of membrane has much larger surface for electronical interconnections and mechanical reliabilities. The initial simulation presented in this report, will provide more insights into how the dimensions of the standing pillar will actually influence the stress distribution along the suspension thin layer of membrane towards Coriolis force input to further optimise the structure for gyroscope application.

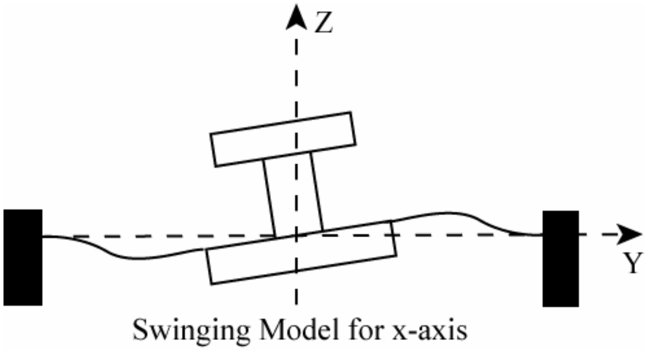

Fig.5. Illustration of swinging model for x-axis

IV. FINITE ELEMENT SIMULATION

The Finite Element (FE) simulation was carried out on the 2-D structure illustrated in Fig. 6. The suspension thin layer of membrane was defined to be clamped along its edges with the outside chip. The descriptions for the symbols to define the dimensions of the structure are shown in Table I.

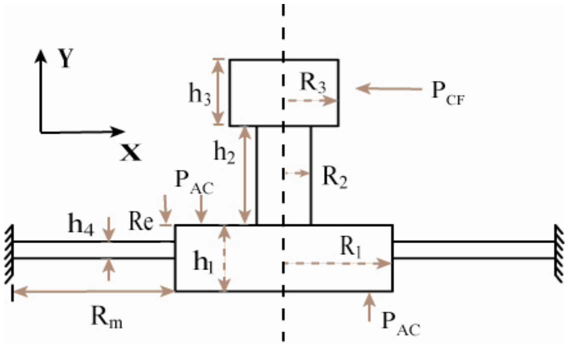

Fig. 6. The implementation structure for FE simulation

TABLE I.

Symbol	Description	Quantity (μm)
h_1	Thickness of Thick Membrane	5
h_2	Height of Pillar	30
h_3	Height of Head	15
h_4	Thickness of Thin Membrane	2
R_1	Radius of Thick Membrane	20
R_2	Radius of Pillar	10
R_3	Radius of Head	20
Rm	Radius of Thin Membrane	40
Re	Depth of Thin Membrane Recess	3
P_{CF}	Applied Pressure from an assumed Coriolis force	5 M Pa
P_{AC}	Applied Pressure from an assumed actuation force	5 M Pa

The applied pressure $\boldsymbol{P_{CF}}$ on the right face of the head of the hammer-shape structure is to simulate the stress distribution on the suspension thin layer of membrane which is caused by Coriolis force, the applied pressure $\boldsymbol{P_{AC}}$ in Fig. 6 is to simulate the electrostatic driving force which would actuate the gyroscope with a swinging model. The simulations were implemented with the applied pressure $\boldsymbol{P_{CF}}$ and $\boldsymbol{P_{AC}}$ separately. By doing this, the comparison between the results would indicate the momentum amplification property of the biomimetic hammer-shape structure. As the the piezoresistive sensing method will be used on the suspension thin layer of membrane of this bio-inspired gyroscope, here we made von Mises stress distribution along the suspension thin layer of membrane as our figure of merit.

Numerical FE modelling and simulation were performed using COMSOL 3.2 finite element software. Due to the symmetrical deformed structure, the left side of the suspension thin layer of membrane was chosen to plot the curves for investigating the mechanical property of the thin layer of membrane, i.e. von Mises stress distribution and deformed displacement caused by the applied pressure, which are shown in Fig. 7 and 8, respectively. The plotted curves clearly indicate that the applied pressure $\boldsymbol{P_{CF}}$, which was defined to simulate the Coriolis force input on the structure, would cause larger von Mises stress as well as deformed displacement on the suspension thin layer of membrane than the applied pressure $\boldsymbol{P_{AC}}$, which was defined to simulate the electrostatic driving force. The result in Figure 5. shows that the biomimetic hammer-shape structure amplifies the simulated Coriolis force input to a level of ~10^9 Pa, a 2-3 order-of-magnitude amplification.

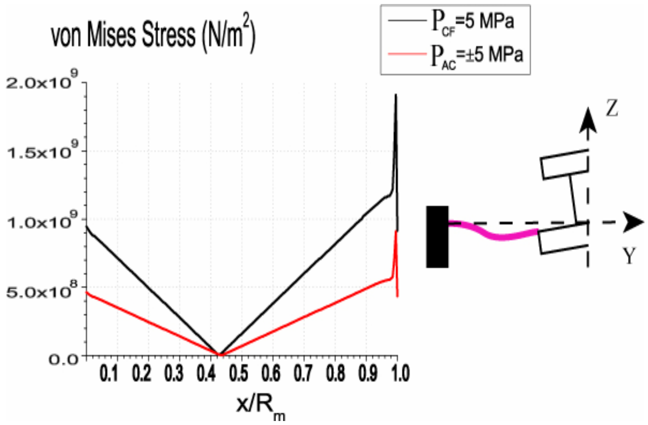

Fig. 7. von Mises stress distribution on the left side of suspension thin layer of membrane

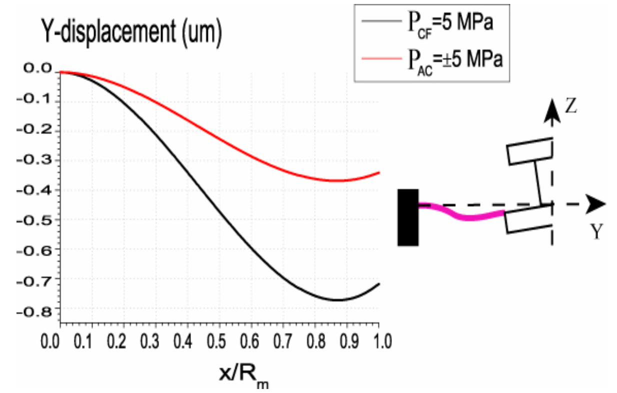

Fig. 8. Deformed displacement in y-axis on the left side of suspension thin layer of membrane

V. FABRICATION

In order to investigate the performance of the bio-inspired gyroscope experimentally, the prototype is being fabricated. Fig. 9 is shown the fabrication flowchart scheme to produce the samples of our design. To make the fabrication process straightforward, surface-micromachining and capacitive transducer were used for the initial devices.

Processing starts with a silicon wafer with a 0.5 µm thin low stress SixNy isolation layer (Fig. 9a.). A 500 nm thin Al layer is sputtered, for the bottom actuation electrodes (Fig. 9b.). A 1 µm sacrificial SiO2 layer is deposited by PECVD for the last etching process (Fig. 9c.). A 300 nm thick SiC layer is deposited by PECVD and patterned to form the membranes and suspension springs, followed by sputtering of another 500 nm Al layer (Fig. 9d.). A 0.5 µm sacrificial SiO2 layer is deposited by PECVD and patterned as a mask layer for the second 500 nm PECVD SiC layer deposition process which is deposed on the middle of the first SiC layer for the thick mass of the gyroscope (Fig. 9e&f.). A layer of SU-8 photo-resist is spin-coated on the wafer surface. The SU-8 resist is illuminated by twice and developed to create hammer-shape structure (Fig. 9g&h.). Processing is completed by wet etching of the sacrificial SiO2 layers, thereby releasing the sensor structures, without affecting the SU-8 hairs (Fig. 9i.).

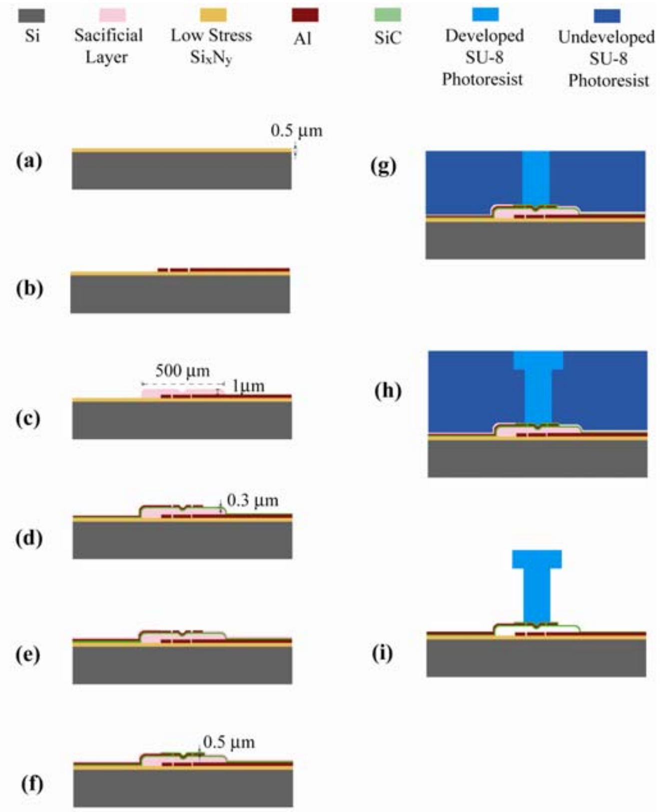

Fig. 9. Process flowchart scheme for the bio-inspired gyroscope

VI. CONCLUSIONS

A new type MEMS vibratory gyroscope is proposed with the inspiration from a real nature gyroscope, i.e. fly's halteres system. The initial numerical modelling based on FE simulation is carried out on the 2-D structure of the preliminary design. The results simulated Coriolis force input and electrostatic driving force have processed and discussed. The fabrication processes for the initial design of the bio-inspired gyroscope based on MEMS technology is presented. With the fabricated gyroscope, the measurement work can be proposed for the next stage of this project.

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