

# Preliminary Study on The Design of A Silicon Bio-inspired MEMS Gyroscope

Yue Chen, Dedy H.B. Wicaksono, Lu-Jun Zhang, and Paddy 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, 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 first report on an on-going work to build a MEMS gyroscope inspired from a natural “gyroscope”, i.e. the *Drosophila* haltere. Halteres are small evolutionarily modified hind wings, 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. Our preliminary work is to model and develop the biomimetics MEMS gyroscope based on the structure of the halteres. A new generation biomimetics MEMS gyroscope was used as the starting point. Several options and stages of possible structural implementations in Silicon are presented. In order to approach the performance of the original biological structure, the structure with a standing silicon post bonded to the center of the substrate mass will be modeled and discussed. We also found that when the gyroscope rotates, the mass suspending beams will be tensile-stressd, compressed and bended according to the fly’s campaniform sensillum inspired Coriolis acceleration. Based on our previous work, the membrane-in-recess microstructure will then be used for the mass suspending beams of the gyroscope structure to enable more sensitive strain detection, so that higher sensitivity Coriolis acceleration detection can be obtained.

**Keywords**— Bio-inspired, Gyroscope, MEMS, Biomimetics

## I. INTRODUCTION

IN recent years, there is an increasing need for the high-performance micromachined gyroscopes. Among many

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micromachined 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]. Micromachined 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. The whole gyroscope system can be very small and inexpensive. In the past few years, there has been a great deal of research on micromachined vibratory gyroscopes [2-5]. Although certain precise Microelectromechanical Systems (MEMS) gyroscopes are commercially available, basically due to the designs, such as package size, power requirements, *etc.*, their applications in micromechanical robotics are still limited.

Wu et. al. in [10] have made their effort to develop a novel piezoelectric angular rate sensor inspired from real flies’ angular rate sensing system for the application in the Micromechanical Flying Insect (MFI). Their simulation and test results indicate that compared with conventional angular rate sensors in MEMS gyroscopes, there are several advantages in using biomimetic haltere sensors to detect angular rate such as lower power consumption and larger dynamic range. However, the authors believe that the sensitivity of the MEMS vibrating gyroscope could be further enhanced by learning the gyroscope found in nature.

Nature has a long history of using highly sensitive gyroscope. Examples can be found in the insect world. Flies, such as *Drosophila* and *Calliphora vicina* (blowfly), use a special vibrating gyroscope called haltere. Halteres are small evolutionarily modified hind wings, which beat anti-phase to the wings and serve a purely sensory function during flight [7]. The *Campaniform Sensilla* and chordotonal organs, which are at the base of the halteres and enable extreme high sensitivity for strain detection [8], encode the strain generated by the Coriolis forces during rotational movements. Therefore, the halteres are very sensitive to Coriolis forces and potentially provide an accurate measure of angular velocity which originates from angular rotations of the body and mediate corrective reflexes during flight [9]. It would be very challenging and fruitful to try to advance the development of new micromachined vibrating gyroscope by taking inspiration from the structure of natural gyroscope, i.e. the halteres.

The objective of this research project is to build a new type of micromachined vibrating gyroscope that has higher sensitivity towards Coriolis force input. The new

micromachined vibrating gyroscope is inspired by halteres of flies and other insects, which act as gyroscopes in those insects. The new micromachined vibrating gyroscope will be implemented in silicon-based Microelectromechanical Systems. The performance of the new gyroscope will be compared with currently existing MEMS vibrating gyroscopes in terms of resolution, zero-rate output (ZRO) and other relevant parameters.

## II. BACKGROUND STUDY

### A. Halteres Morphology

The structure of fly's halteres is shown in Fig. 1 and Fig. 2. Each haltere contains approximate 400 mechano-receptors [13], mainly campaniform sensilla and chordotonal organs, embedded in the flexible exoskeleton at the haltere base. Derham [14] was the first scientist to note that with their halteres removed, flies cannot keep stable 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 [15]. During flight the halteres beat up and down in vertical planes through an average angle of nearly  $180^\circ$  anti-phase to the wings at the wing beat frequency. In addition, the two halteres are not coplanar so that flies can detect rotations about all three turning axes [16] [17].

The nerve control-loop of a fly's haltere system is shown in Fig. 3. Motoneurons are indicated by heavy lines. The

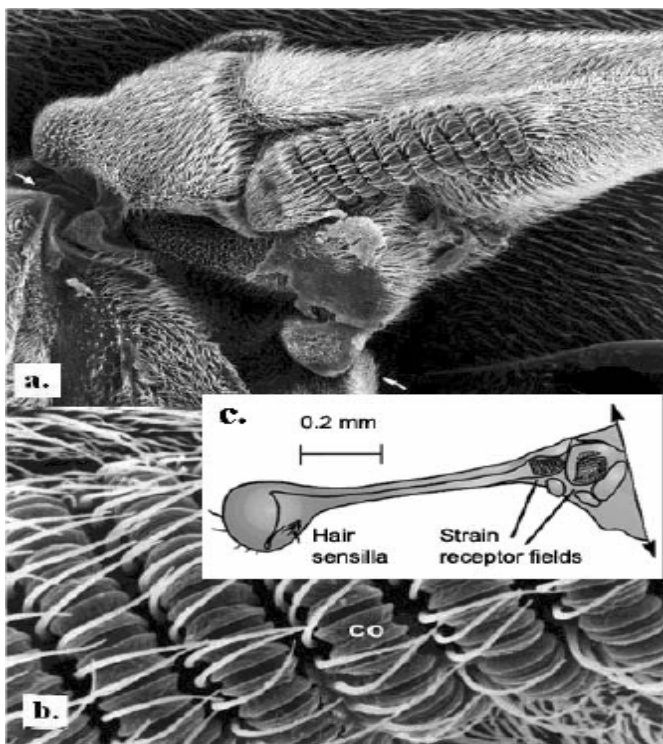


Fig.1. **a.** Ventral field of campaniform sensilla on the base of left haltere of the *Calliphora* ( $\times 300$ ). Plane of oscillation is toward the observer. **b.** Rows of *Campaniform sensilla* on the haltere. The caps are hidden beneath the semicircular collars ( $\times 1300$ ). **a.** and **b.** Source: [11]. **c.** Left haltere from above. Most of the mass of the haltere is in the knob (left). Source: [12].

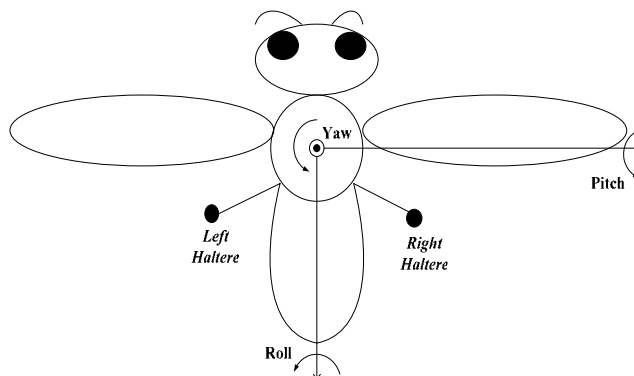


Fig. 2. Schematic picture of enlarged halteres of a fly. Modified form [10].

descending visual interneuron activates the haltere control muscles to change haltere kinematics during flight. This change in haltere beating would in turn activate haltere campaniform neurons which feed forward to wing-steering motoneurons. In such a way, visual interneurons could influence wing control muscles without any direct connections (dotted line) with those wing motoneurons.

Theoretical modeling of the haltere force has been discussed in [16]. As a result of fly motion and haltere kinematics during flight, a complex force acts on the halteres. Assuming no translational motion of the insect, this force can be expressed in vector notation as following:

$$F = mg - ma - m\dot{\omega} \times r - m\omega \times (\omega \times r) - 2m\omega \times v \quad (1)$$

where  $m$  is the mass of the haltere,  $r$ ,  $v$ , and  $a$  are the position, velocity, and acceleration of the haltere relative to the insect body, respectively,  $\omega$  and  $\dot{\omega}$  are the angular velocity and angular acceleration of the insect, and  $g$  is the gravitational constant. When fly's body rotates, centrifugal ( $-m\omega \times (\omega \times r)$ ) and Coriolis ( $-2m\omega \times v$ ) forces are produced on its halteres. However, the influence of the centrifugal force to the rotation movement can be neglected.

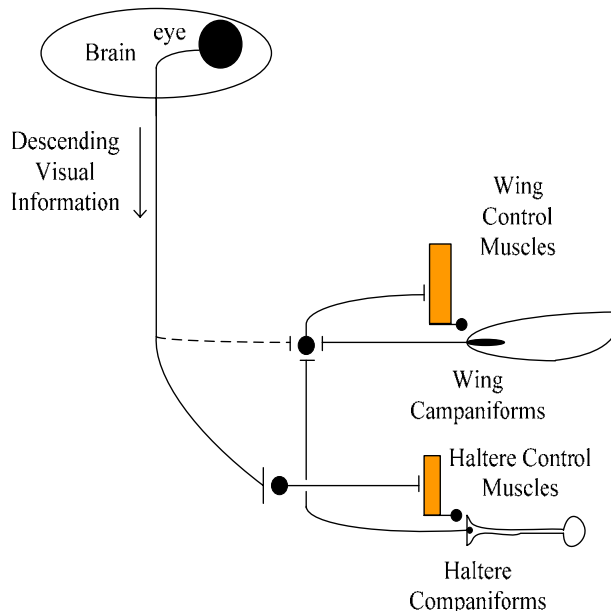


Fig. 3. Scheme of the nerve control-loop of a fly's haltere system. Modified from [9].

Firstly, the centrifugal force is generally smaller than the Coriolis force and mostly in the radial and tangential directions. Secondly, as it is proportional to the square of angular velocity of the fly, the sign of rotations would not be influenced by the centrifugal force. Thirdly, on the other hand, the Coriolis force is proportional to the product of the angular velocity of the fly and the instantaneous haltere velocity. The Coriolis force has components in all three directions and contains the information on the axis, sign, and magnitude of the fly's body rotation. The angular acceleration force ( $-m\dot{\omega}\times r$ ) is proportional to the product of the angular acceleration of the fly and the instantaneous position of the haltere. Due to the  $90^\circ$  phase shift, the angular acceleration and the Coriolis force signals are separable. The primary inertial force ( $-ma$ ) depends on the haltere acceleration relative to the fly's body. This force is orders of magnitude larger than the Coriolis force and also has only radial and tangential components. The gravitational force ( $mg$ ) is always constant and depending on the haltere position and the fly's body attitude in space, and its distribution varies in the three directions. However, because it is a tonic lateral component, the effect of this gravitational force on the angular velocity sensing is negligible. For this reason, the gravitational force can be considered as DC offset on the Coriolis force and can be removed easily by the subsequent signal processing step.

### III. DESIGN AND DEVELOPMENT STRATEGY IN MEMS

Biological research has demonstrated that fly's haltere system is playing an indispensable role for its impressive maneuverable and elaborate flight behaviors [14][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 (*complaniform sensilla*), and visual control system [9]. Each organ has its unique structure, functions and consists of different materials with different mechanical properties. The implementation of the new gyroscope in silicon structure will be carried out in stages. The first and easiest stage will be silicon structure with least similarity to the original haltere structure, still with pillar rotary movement to detect the Coriolis force. 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 *complaniform sensilla* [18].

#### A. Pillar Rotary Structure

The first implementation in Silicon is trying to imitate the haltere structure. This stage is shown in Fig.4. By considering the limitation in current microelectronics-compatible MEMS fabrication, this first stage mimics was designed without a round shape mass at the head of the silicon pillar. The piezoresistive material at the base of the pillar imitates the strain receptors. Driving can be electrostatic or electromagnet methods, and sensing can be done by using piezoresistors.

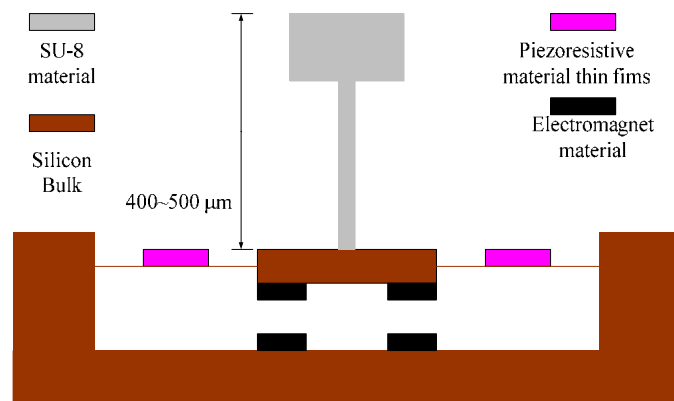


Fig. 4. First implementation stage in Si-haltere structure.

#### B. Improved Pillar Rotary Structure

According to the modeling and simulation for the haltere structure [10], the key parameters for the design are the haltere length, mass, velocity and stroke amplitude. In order to filter the influence of inertial forces, a wide face of the pillar in the plane of it beating is also necessary [10]. Due to the thickness of conventional silicon wafer ( $525\mu\text{m}$ ) and

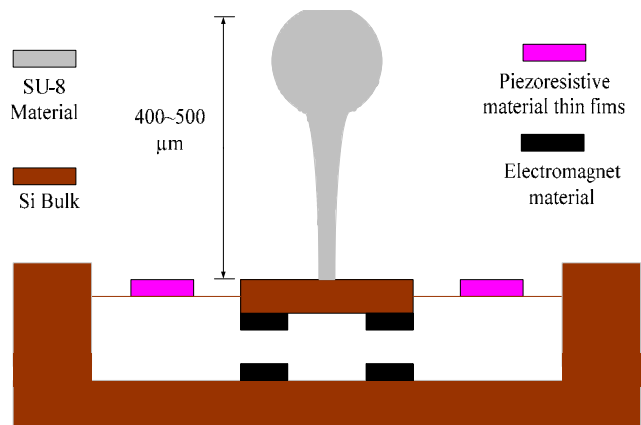


Fig. 5. Second implementation stage in Si-haltere structure.

fabrication process, it is difficult to make the length of the pillar longer than  $500\mu\text{m}$ . However, in order to improve the performance of the gyroscope, efforts are made to guarantee a pillar with relatively heavy mass as well as wide surface. As shown in Fig.5, a structure with a round-head pillar has been designed. The electromagnet driving can be implemented around the pillar and piezoresistors can be used to sense Coriolis force.

#### C. Electrostatic Pillar Rotary Structure

The bio-inspired vibration gyroscope with pillar rotary structure can also be implemented with electrostatic driving and sensing methods, which is illustrated in Fig.6. The structure is simpler than other ones, but due to the need for inertial and Coriolis forces separation, its driving and sensing model should be designed carefully.

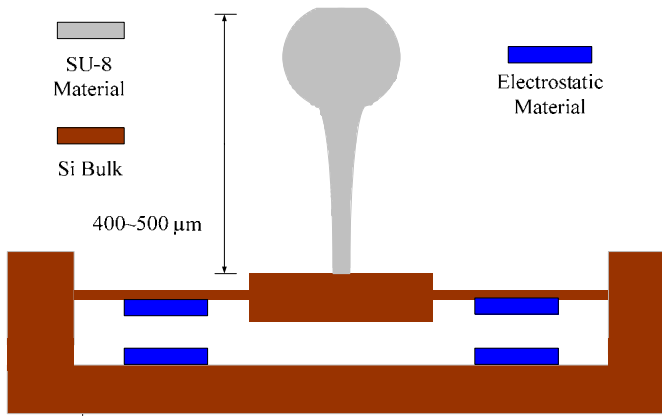


Fig. 6. Third implementation stage in Si-haltere structure

#### D. Use of the biomimetic strain sensor

The previous work of one of the authors [18] has showed a biomimetic strain sensor inspired from *complaniform sensillum*, that can achieve high strain sensitivity by its novel strain amplification structure. By replacing the conventional piezoresistors with the biomimetic strain sensor, authors believe that the sensitivity for the Coriolis force of this bio-inspired MEMS gyroscope can be improved dramatically.

#### IV. COMMENTS AND DISCUSSION

Certain MEMS vibrating gyroscopes with metal pillar rotary structures have already been designed and fabricated [19][20]. As shown in Fig. 4, the rotary movement of the pillars is induced by four electromagnets. When the angular rate is applied to the micro gyroscope, Coriolis force induces a change of stress in the beam. The micro gyroscope detects the difference of stress variation in the beam via the piezoresistors. It is also believed that the pillar used in those gyroscopes can provide Coriolis acceleration amplification [20].

At current stage, efforts are still being made to get sufficient simulation results to support our hypothesis and initial design inspired in the background knowledge. In fact, rather than elucidating the sensing mechanism in the halteres, the goal of this research project itself is to make a better MEMS vibratory gyroscope than currently existing ones.

It is certainly possible to adjust our designs to comply with the real fly's gyroscope, i.e. halteres system, with some improvement strategies. Examples can be taken, such as to apply an array of biomimetic strain sensors at the base part of the silicon pillar, which will be like the real nature halteres structure.

Except design the dimensions of the pillar rotary structure with carefulness, another option to improve the sensitivity of the vibratory gyroscope is to use electro-mechanical feedback schemes with sophisticated electronics [21]. Meanwhile, the bandwidth can also be efficiently expanded without increasing the thermo-mechanical noise equivalent rate signal.

Attention should be paid that in the engineering point of

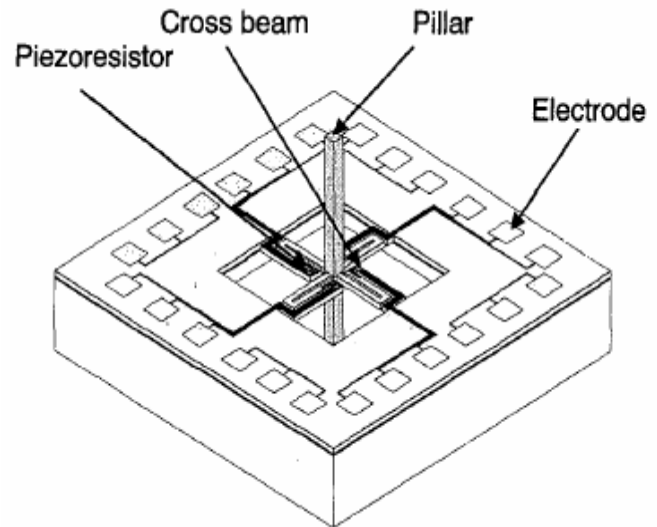


Fig. 4. Structure of the piezoresistive rotary movement micro gyroscope. Source [19].

view it is always not the sagacious way to make the sensor to be 100% copy of the structure in nature. Further elucidation of the driving and sensing mechanism in nature itself is important to build a better MEMS vibratory gyroscope inspired by the natural biological gyroscope.

#### V. CONCLUSIONS

A new type MEMS vibratory gyroscope is proposed with the inspiration from a real nature gyroscope, i.e. fly's halteres system. However, how to completely achieve the mechanical behaviour of the natural structure of halteres system has not yet been completely understood, further simulation is necessary. Nevertheless, we intend to make the new MEMS vibratory gyroscope based on the known advantageous properties of the halteres system, in parallel with this mechanism elucidation. Future possibilities for the application of such precision gyroscopes are infinite, including for example, application in robots, Micromechanical Flying Insect fly [15] and space engineering [20].

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