Robust Angular Rate Sensor based on Corona Discharge Ion Wind

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***Abstract* - A new design of a jet flow gyroscope is developed by employing the advantages of a corona-discharge-based jet flow. Ion wind is generated by applying a high–voltage between a pin, as the discharge electrode, and a ring, as the reference electrode. When the gyroscope is subjected to an angular rate, the induced Coriolis force deflects the ion wind. This deflection is detected using four hotwires installed downstream of the working chamber behind the reference electrode. Both the experimental and numerical study have been conducted to study the phenomenon. The results show that the angular rate can be detected with a sensitivity of above 15 µV/º/s. Because ion wind can be generated with minimum power and does not require any vibrating components, the device is robust, consumes low power, and cost-effective.**

I. INTRODUCTION

The main principle of gyroscopes is based on the effect of the Coriolis acceleration in the vibration of a reference proof mass. In spite of high measurement performance as well as recent advancements in design and fabrication technology for these devices, gyroscopes with vibrating proof masses are fragile due to the oscillation of the mass element. Meanwhile, fluidic-based gyroscopes, where the reference movement comes from fluidic media, instead of a solid-state structure, do not require a proof mass, and therefore, do not suffer from any corresponding disadvantages.

Several techniques are used to generate flow for fluidic-based inertial sensor, including the natural-convection-based method from a locally heated region [1]–[7]; the method based on thermal expansion, which is induced by quickly heating gas; the method based on jet flow using conventional pumping approach such as using PZT membrane [8], [9]; jet flow can be generated from an electro-conjugate fluid using a high electric field created by a high voltage applied on electrodes submerged in liquid [10]. A gyroscope utilizing jet flows eliminates the effect of linear acceleration by force convection [11].

Another method to create jet flow is utilizing ionic wind. Many researchers have been attracted to apply the corona discharge phenomenon in various areas [12]–[17] and including synthetic jet design [18]–[25]. With these applications, an electro-hydrodynamic (EHD) flow, also called ion wind, can be generated using high voltage corona discharges. The application of EHDs yields several distinguished advantages such as low weight, simplicity, robustness, lack of moving parts, and low power consumption. Hence, EHD is considered as a potential method that is supported by recent technological advances in microfabrication [26], [27]. In this spirit, ionic wind corona discharge can be applied to develop angular rate sensors, where a flow is able to freely vibrate in three dimensional space under inertial forces.

Although the idea of using ion wind in this application has been mentioned previously [28], not much technical documentation has been represented so far. Furthermore, the requirement of a jet flow inside small spaces yields a challenge in manufacturing this kind of gyroscope, therefore many designs do not mention the flow generating components, or simply rely on external flow sources [29]. In this work, a relevant design of an ion wind generating device and its application in angular rate sensing is presented.

II. DESIGN AND SIMULATION

Design of the proposed sensor is presented in Fig. 1. In a point-ring configuration, the average velocity (U) of ion wind is estimated, from the discharge current, as follows.

$$U = \mathrm{k}\sqrt{I/\rho\mu}, \qquad (1)$$

where k is the coefficient and depends on the electrode discharge area and the inter-electrode distance, $\mu = 1.6\times10^{-4}$ $\mathrm{m^2\cdot V^{-1}\cdot s^{-1}}$ the

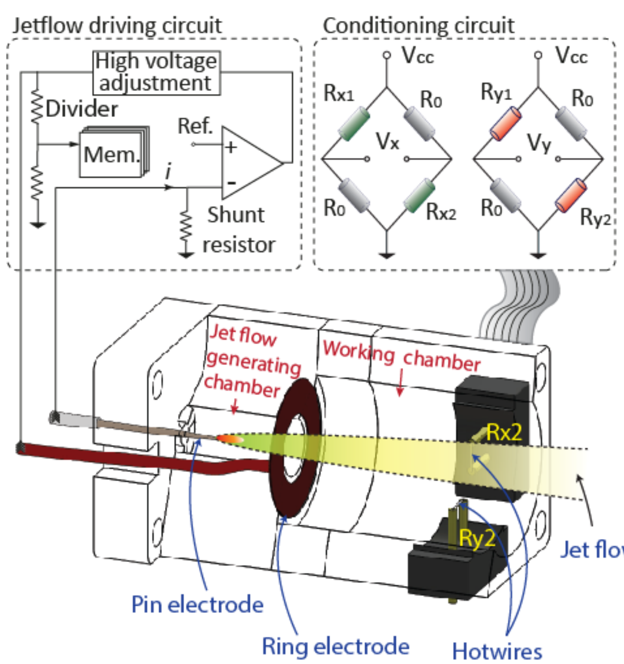

Fig. 1. Design of the angular rate sensor based on corona discharge ion wind and the schematic of the monitoring and sensing circuit.

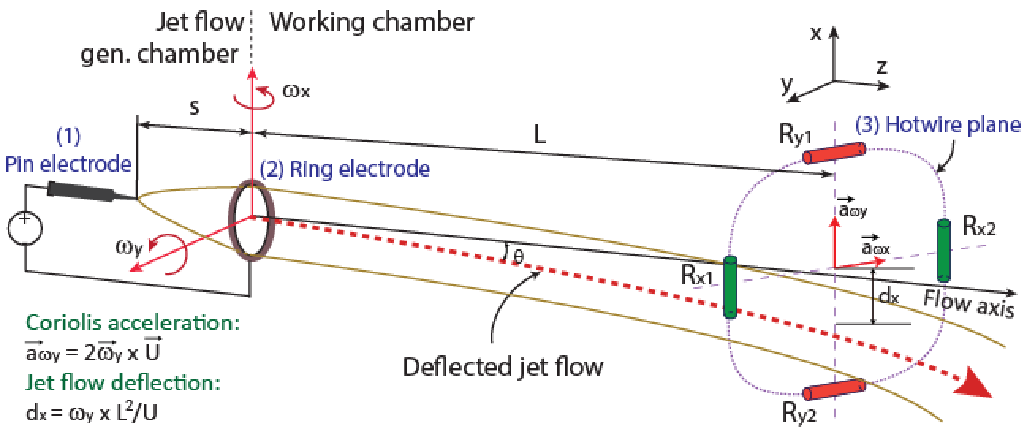

Fig. 2. Principle of the ion wind gyroscope.

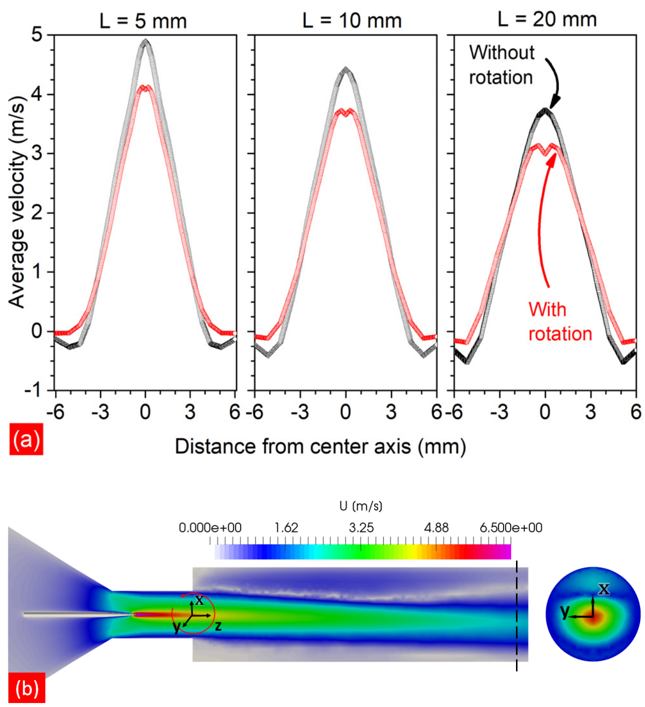

Fig. 3. Simulation results: (a) Velocity profile *Uz/x* of jet flow on the cross-section of the jet flow chamber at different positions (L = 5, 10, and 20 mm) along z axis when the device is at rest (black lines) and when rotating with an angular velocity ω_y = 5 rpm (red lines); and (b) velocity contour of the device with an angular velocity ω_y = 5 rpm.

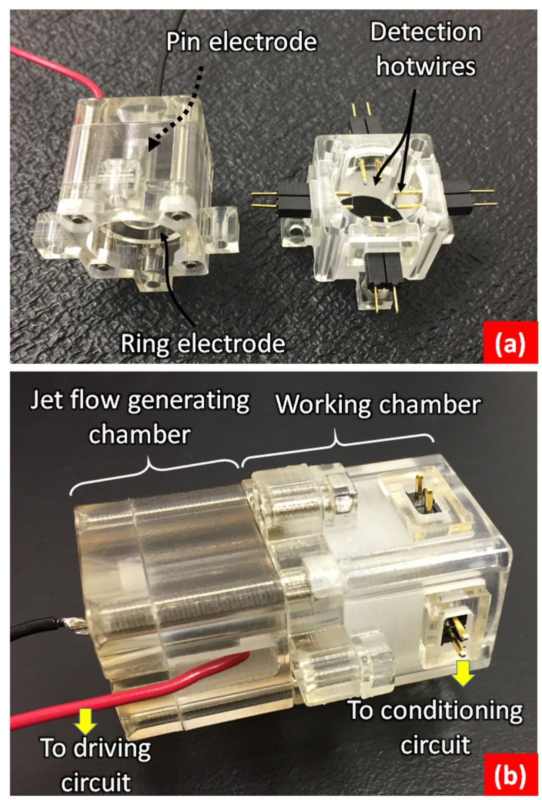

Fig. 4 Fabricated prototype.

ion mobility, ρ = 1.2041 kg·m^{-3} the air density and I the discharge current in µA.

Once flow is generated in the device mounted on the rotating frame, it is affected by the Coriolis force. Indeed, the effect of the rotating frame on the flow is overwhelmed by the strong electric field that handles the flow along the distance from the pin electrode to the ring. After passing through the ring electrode in the working chamber, the flow is deflected by the Coriolis force as shown in Fig. 2. Inside the working chamber, this deflection is detected using four hotwires placed at a distance L from the ring center.

For a hotwire heated by an electric current i_{hw} and subjected to a variation of cooling air velocity ΔU_{ω}, the temperature variation of the hotwire is converted into a relative variation of resistance as follows:

$$\Delta R_{\omega} = \frac{\lambda \pi l \alpha i_{hw} R_{HW0}^2}{\left(\lambda \pi l Nu - i_{hw}^2 R_{HW0} \alpha\right)^2} \cdot \frac{\rho \mu n Nu}{I k^2} \cdot \beta L^2 \omega \qquad (2)$$

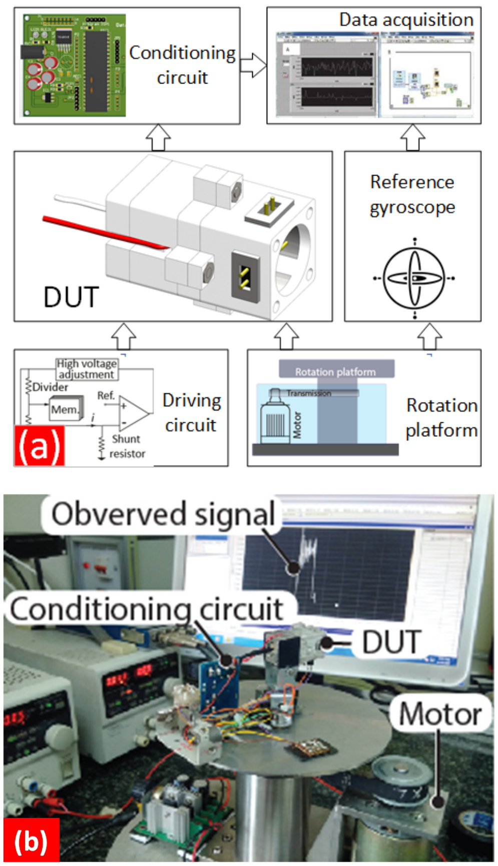

Fig. 5. Experimental setup. (a) Block diagram, (b) actual setup.

where l is the typical length of the hotwire, α the temperature coefficient of the resistance, and R_{HW} the reference resistance of the hotwire, λ the thermal conductivity of the air; and Nu the Nusselt number representing the heat transfer coefficient between air flow and the hotwire. The proposed sensor first was simulated using OpenFOAM. Then, a prototype of the sensor was fabricated using rapid prototyping technology and the performance of the sensors was characterized.

III. Results and Discussion

The simulation is conducted for the case the device rotates with an angular velocity of ω_y = 5 rpm around Y axis. The velocity contour shown in Fig. 3b depicts that the flow deflects downward. Furthermore, the velocity profiles $U_{z/x}$ of jet flow at five positions L = 5, 10, and 20 mm from the ring electrode in Fig. 4a show that the deflection of jet flow gradually increases at the further positions from the nozzle. Therefore, with rotation about y axis, the flow deflects downward and the velocities of jet flow at the two hotwires R_{x1} and R_{x2} (see Fig. 2) change oppositely.

Fabricated prototype of the sensor and experimental setup are depicted in Fig. 4. The experiment works with a corona discharge voltage of 5 kV and X hotwires heated by a current i_{hw} of 150 mA. The output voltage is offset to initial values when the turntable is at rest. Fig. 5 depicts the output voltages on hotwires X_1 and X_2 recorded with respect to time when the turntable rotates at different speeds. Results show that the output voltages on hotwire X_1 and X_2 are in opposite value and the

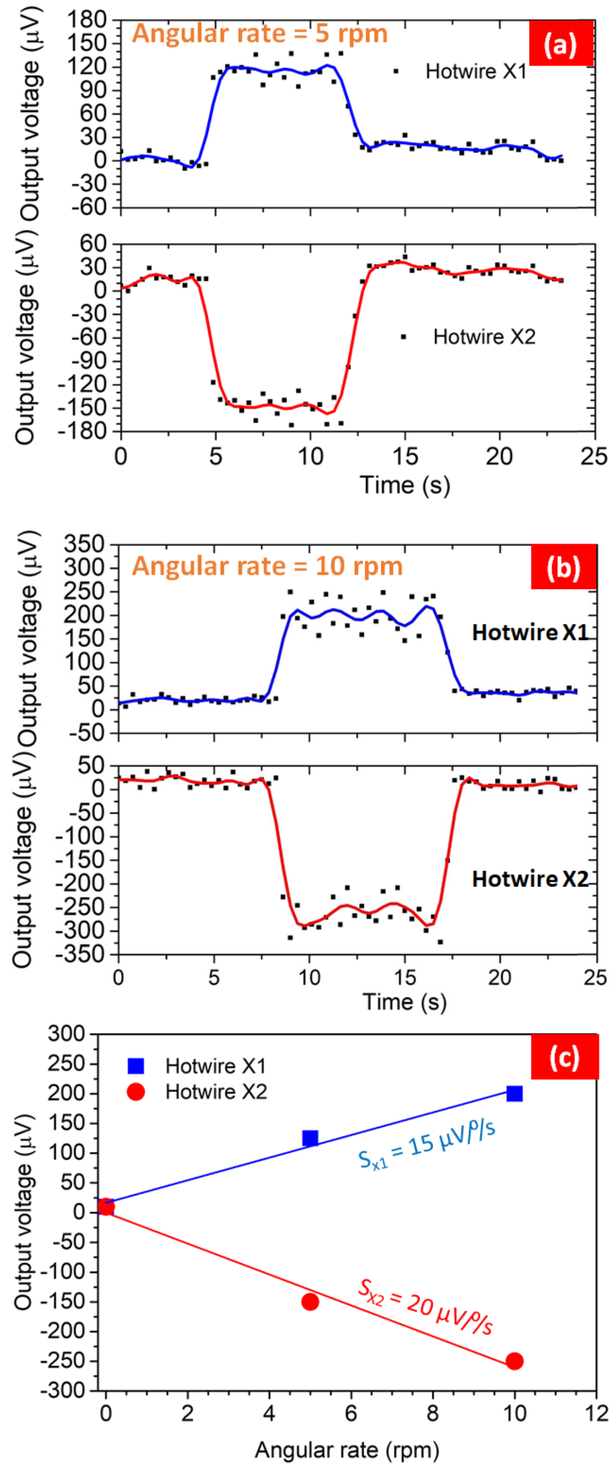

Fig. 6. Measurement results. (a) Output voltage change on hotwires X1 and X2. (b) The time dependent output voltage measured at hotwires X_1 (top) and hotwire X_2 (bottom) by the experiment with a rotation of turntable of 10 rpm.

output voltage changes linearly with the applied angular rate. The sensitivity of the hotwires X_1 and X_2 are 15 µV/°/s and 20 µV/°/s, respectively. The different in sensitivities of the hotwires can be explained by the symmetry of the ion wind and the linear relationship of the velocity of ion wind flow versus the distance from the flow center to the position of hotwires.

IV. CONCLUSIONS

We have reported a new design of jet flow gyroscope using ion wind corona discharge by a numerical simulation and experimental analysis with the configuration of pin – ring electrodes. The deflection of ion wind jet flow by the Coriolis force from the angular rate is detected with a sensitivity of 4.7 µV/°/s. The device is robust because the new structure does not require any vibrating component using instead the characteristic of ion wind jet flow. Furthermore, due to low energy consumption, a small battery can be used for the present ion wind gyroscopes. Finally, another benefit of this work is to contribute to valuable sensing techniques and the manipulation of fluidics for multidisciplinary fields such as microfluidics, analytical chemistry, and a "lab-on-a-chip".

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