STUDY ON POINT-TO-RING CORONA BASED GYROSCOPE

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ABSTRACT

We present for the first time a novel gyroscope using circulatory electro-hydrodynamics flow in a confined space. Three point-ring corona actuator is to generate ionic flows in three separated channels and the ionic flows then merge together at a nozzle of the main chamber to create a jet flow. The residual charge of ion winds is removed by a master-ring electrode. By the effect of angular rate, the jet flow handled by a hotwire anemometry is deflected and sensed. Results by both experiment and numerical simulation consistently show good repeatability and stability of the new configuration-based device. Since ion wind is generated by a minimum power, the device does not require any vibrating component, thus the device is robust, low cost and energy consumption.

INTRODUCTION

Ion wind based Electro-hydrodynamic (EHD) flow possesses several advantages including lower cost and energy consumption, tidy and light but solid structure and simple operation. Hence, EHD is a potential method supported by technological advances in microfabrication [1][2]. The jet flow based on this approach was recently applied in airflow control [3][4]; propulsion technology [5]–[7] [8] and bio-electronic device [9]. In this paper, ionic corona is used to develop angular rate sensors in 3D space where a flow vibrates by an inertial force.

Recently, our group has developed inertial sensing application in an open system with regard to the advantages of ion wind corona-discharge using the pin-ring electrode configuration [10]. Since the device does not require any vibrating components, the ion wind based devices possess several advantages including tidy and light but solid structure without moving parts and simple operation compared comparison with other methods using air pumps [11] or oscillating pistons [12]. In addition, lower cost and energy consumption are also strong points of the method.

In a confined system the circulatory flow is one of the prerequisites in developing a reliable angular rate sensor in a confined system, so several techniques to generate a jet flow were developed. For example, vibration using a lead zircona-titanate diaphragm [13]–[15], activation by electrohydrodynamics in a high electric field using an electro-conjugate fluid [16] or by the natural convection from a locally heated region where a jet flow

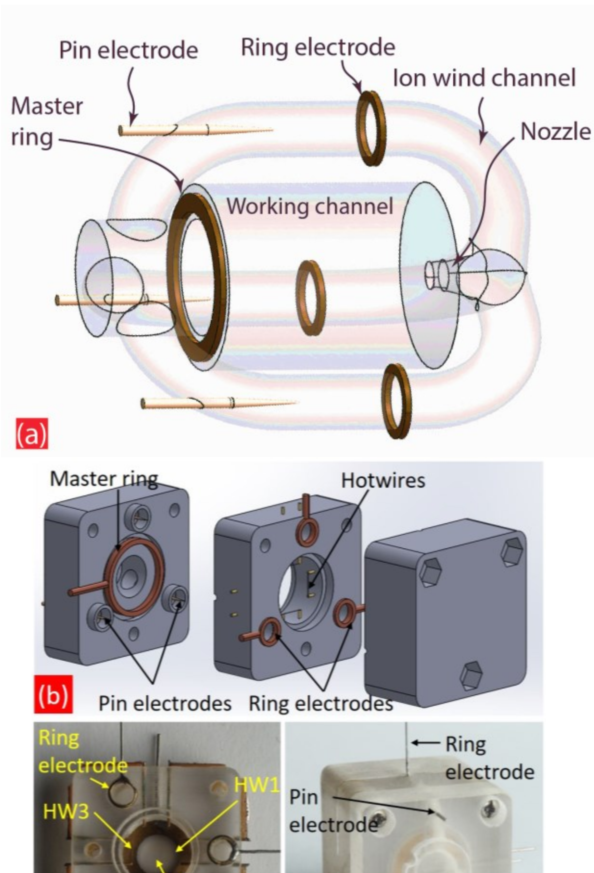

Figure 1. *Present point-to-ring corona based gyroscope: (a) Schematic design, (b) 3D sketch and (c, d) experimental prototype.*

moves along the direction of mass diffusion [17].

For the ionic flow approach, a jet flow can be created by different configurations of electrodes. For example, using needle-to-ring electrodes where pin plays the role of the corona electrode and ring as the collector. For this configuration, ion wind is partially neutralized when it reaches to a high velocity near the surface of the ring. However, the integration of ionic wind into the circulatory flow results in the residual electric charge in closed systems. This yields a reversed electrical field and then

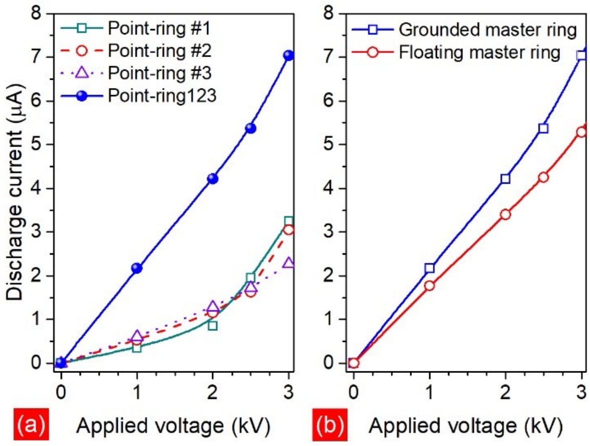

Figure 2*: I-V characteristics of system: (a) I-V characteristics of point-ring 1, 2, 3 and the system with floating master ring; and (b) I-V characteristics of all three pairs of pin-ring electrodes inside ion wind chambers with grounded master ring and floating master ring.*

causes critical damage to the corona discharge process. Although this problem can be solved by introducing embedded neutralizing components or grounded into the system, it leads to complicated structure and/or designing process.

This work is a further development of the ion wind based closed system [18] using multiple point-ring electrodes for inertial sensing applications. A novel configuration is developed by introducing a master ring to neutralize the residual charge. Together with experimental work, numerical simulation for the new device using our OpenFOAM self-developed solver is carried out to investigate the reliability of the present approach. The application of this device in sensing angular rate is also demonstrated.

DESIGN AND EXPERIMENT SETUP

The present symmetric flow network consists of three cylindrical chambers (named ion wind chambers) which are connected together before linked with a working/sensing chamber through a nozzle at the system center where hotwires are installed (see Fig. 1). The dimensions (diameter d × length l) of the ion wind and working chambers are 5 mm × 10 mm and 12 mm × 15 mm, respectively as designed in the simulation model. In each ion wind chamber, a pin-ring configuration is installed and plays the role of an actuator of ion wind. A pin of stainless steel SUS304 with 0.4mm diameter and a spherical pin tip of 80 µm radius is located at an optimized distance from the ring. For the sake of easy assembly, a pin length of 8mm is used in this work. A master ring of SUS304 with dimensions of 6 mm × 10 mm × 0.1 mm (inner diameter × outer diameter × thickness) is set up in the sensing chamber.

By a high voltage applied between pin-ring electrodes, ion wind flows generated in the three ion wind chambers drive air flows in chambers moving toward a nozzle. The merged air flow then propagates through the working chamber before it is diverged into three components in the ion wind chambers where they are repeatedly accelerated. Such process of merging and separation of flows is repeated to create a circulating flow inside the system as schematized in Fig. 1(a). After each cycle of the propagation, the velocity of flow in the working chamber gradually increases until reaching a stable state. As we know, an integration of ion winds into the circulatory flow produces the residual electric charge in the closed system. This yields a reversed electrical field and then results in critical damage to the corona discharge process. Thus, a grounded master ring is installed inside the working chamber to neutralize the merged flow before it is separated and return into the ion wind chambers.

A source of high voltage supplied by Glassman EH10R10 is applied between pin-ring electrodes as presented in Fig. 4 and a micro-Ampere-meter M244T41 with scale of 10 µA is set up to measure the current variation of the system.

RESULT AND DISCUSSION

Figure 2a shows the current-voltage (I-V) characteristics of three pin-ring electrode pairs and each of them using a master ring meanwhile Fig. 2b gives the comparison between the I-V characteristics of three pin-ring electrode pairs with and without the use of master ring.

Experiment results find that while the master ring is activated by connecting with the ground, a discharge current goes through the master ring with a high voltage applied between the pin-ring electrodes. The discharge current of the system is much lower when master ring is connected to the ground. Moreover, this effect of master ring increases with the increase of voltage applied on ping-ring electrodes. In other words, there is a significant effect of the master ring on the I-V characteristics of each ping-ring circuit and the system.

In particular, results in Fig. 2b show an increase of more than 25% in discharge current with the use of master-ring. Furthermore, the I-V characteristics of three pairs of pin-ring electrodes located inside ion wind channels presented by the three bottom curves (Fig. 2a) are the same. A numerical simulation of the ionic flow in which the measured I-V characteristics are used as the boundary condition of discharge demonstrates the ion flow mechanism as presented above.

The simulation of ionic flow performed in OpenFOAM environment is a multi-physical problem which relates to (i) an electrical field inducing the migration of ions within the inter-electrode region as well as their interaction with the air flow in chambers; and (ii) the motion of air flow in channels. Ion winds generated by pin electrodes move under the effect of electric field and driving air flow which, in turn, redistributes itself across the domain under consideration.

On the electrical field, the corona discharge is set up as a boundary condition on the electrodes. Assuming that the charge density q_s on electrodes' surface is determined as a function of the discharge current I $q_s = I/(\mu E_{\text{on}} A)$ by the I-V characteristics, where A is the total area of electrodes. An electric field generated on electrodes is greater than the onset E_{on} = 3.23×106 V/m. Meanwhile, the potentials on the pin and ring electrodes are equal to the applied voltage V and 0, respectively. The Neumann condition is set up at the edges of the model.

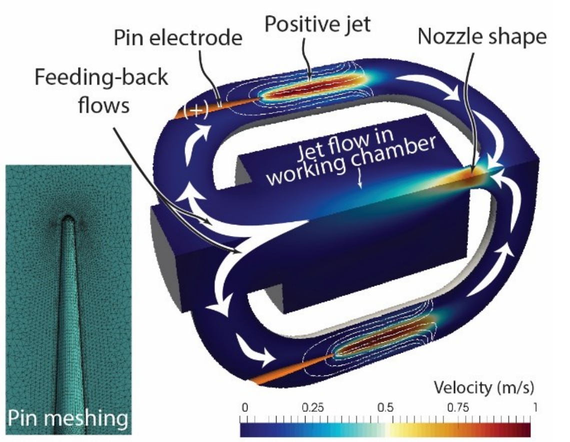

Figure 3: *Simulation showing flows circulating inside the sensor using OpenFOAM.*

Neglecting the permittivity gradient, dielectrophoretic and electrocostriction forces, only the Coulomb force given by $f_e = q\vec{E}$ is introduced into the Navier–Stokes equation for the incompressible air flow.

Fig. 3 presents a cut view of flow illustration in the device. It describes a flow generated from corona actuator circulating back to the pins through the three secondary channels. In the working chamber, the air flow maintains the jet form when getting out of the nozzle.

Experimentally, the flow velocity is measured using a hotwire heated by a current of 0.2 A. Fig. 4 shows the time evolution of output voltages measured on two hotwires located surrounding the jet flow axis (Fig.1). Results show a sharp increment of the output voltage when the discharge voltage on pins reaches to 2.5kV, corresponding to a discharge current of 5.4 mA. This can be explained by an increasing of ion wind corona discharge which accelerates air flow through hotwires and then increases the thermal convection between hotwires and air flows. This convection reduces the temperature on hotwires, yielding an increase of their voltages (U_{hw}) (see Fig. 5)

It is worth noting that the average output voltage on four hotwires is tested for two cases of grounded and floating master rings. Observed results depict a significant impact of master ring on the ion wind and the air flow velocity inside the working chamber. With a given applied voltage, the intensity of ion wind is stronger when the master ring is grounded. This observation is in agreement with the I-V characteristics of the master ring as presented in Fig. 2.

The capability of the present device to detect angular rate is demonstrated using our developed turntable whose configuration can be found in our recent publication [19], [20]. The turntable whose angular velocity is monitored by an integrated encoder (Tsukasa Electric Ltd) is driven by a direct current motor. The present device mounted at the turntable center is connected to an outer circuit through a slip-ring mechanism installed along the center of the turntable. This installation allows the electrical system working safely while the turntable is rotating. A high voltage provided to the device is also set up through the slip-ring. In this work, the present device is horizontally mounted on the turntable with the maximum angular

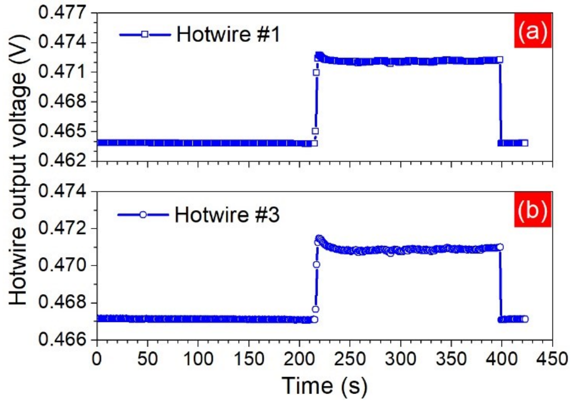

Figure 4: *Experiment works: Time evolution of output voltage on two hotwires with a high voltage applied to the point-ring electrodes.*

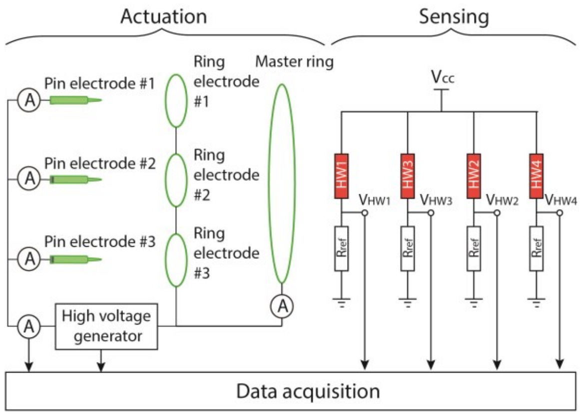

Figure 5: *Experiment works: circuit set up to measure output voltage on hotwires.*

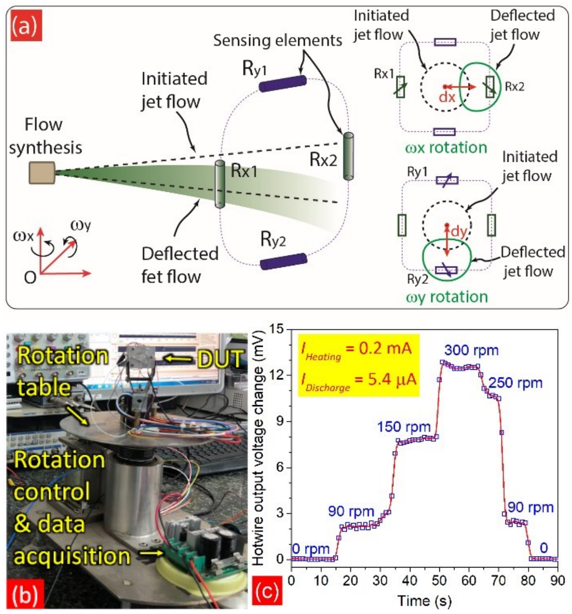

Figure 6: *Experiment work on angular velocity measurement: (a) Mechanism of jet flow gyroscope, (b) Experimental setup and (c) Hotwire voltage plotted vesus rotation angle.*

velocity of 300 rpm. Due to the Coriolis acceleration, the rotation of the turntable deflects the flow in the working chamber (Figs. 6 a, b).

Without the presence of ion wind, the zero-output voltage measured on hotwires by Fig. 6c depicts that the turntable motion does not impact on the air flow as well as the temperature of hotwires in the sensing chamber. In other words, the environment does not influence on working condition of the present closed system.

The angular sensing rate of device on turntable center plotted versus different speeds by Fig. 6c shows a deflection of jet flow inside the main chamber, yielding changes of hotwire temperature. The variation of output voltage on hotwires with a range of the turntable velocities (90 rpm, 150 rpm, 250 rpm, 200 rpm and 90 rpm) confirms the stability and repeatability of the device with a scale factor of around 44 µV/rpm.

CONCLUSION

We have reported a new design of jet flow gyroscope using ion wind corona discharge with the configuration of pin – ring electrodes. For this configuration, a three point-ring corona actuator is to generate ionic flows in three separated channels. The ionic flows merge together at a nozzle of the main chamber to create a jet flow. The residual charge of ion wind is removed by a master-ring electrode. The numerical analysis and experimental results demonstrated the feasibility and performance of the present device. In addition, the device is robust because its new structure does not require any vibrating component. Furthermore, due to low energy consumption, only a small battery can be used for the present ion wind gyroscopes.

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