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Concept of a Liquid Rate Gyroscope using an Electro-conjugate Fluid

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Abstract— **We propose a novel liquid rate gyroscope using an electro-conjugate fluid in this study. The electro-conjugate fluid (ECF) is a dielectric fluid that works here as a functional/smart fluid generating a powerful jet flow (ECF jet) when subjected to high DC voltage. Using the ECF jet, we developed a liquid rate gyroscope based on the principle of a conventional gas rate sensor operated by Coriolis force. Because the ECF jet is generated only with a tiny electrode pair, the pumping part of proposed ECF gyroscope needs no mechanically moving parts, resulting in making the ECF gyroscope suitable for micro sensor compared to the gas rate sensor having a pumping mechanism inside. We fabricated a prototype of liquid rate gyroscope (40mm × 60mm × t7mm) and confirmed its characteristics by experiment. The experimental results confirm the effectiveness of the proposed liquid rate gyroscope. The scale factor of -29 mV/(°/s) is obtained with applied voltage of 4.5 kV.**

I. INTRODUCTION

A gyroscope is one of the most important mechanical components, used in wide variety of mechanical systems such as rockets, aircrafts, industrial robots, automobiles, etc. Gyroscopes used for aerospace field generally have high accuracy but are relatively bulky and costly compared to those used in industrial robots and automobiles. Fig. 1 summarizes a performance vs. price relation for many types of gyroscopes [1]. Ring laser gyroscopes have higher accuracy but costly. On the contrary, vibration gyroscopes are widely used because of its low price but having low accuracy and some problems.

In late years, gyroscopes are paid much attention as their application area is expanding to consumer products like camera shake corrections, car navigation systems, traction control systems, etc. In such applications, the accuracy might not be required high, but features like low cost, long life time, resistance to impact/vibration are required for gyroscopes. For the consumer product applications, there have been many kinds of micro gyroscopes [2-4]. Among them, vibrating gyroscopes are now widely used for above mentioned consumer product application because it is small in size and costs low. However, vibrating gyroscopes have vibrating elements inside resulting in making them not robust for impact/vibration. Hence, it could be a new standard for a convenient gyroscope if there were a novel small-sized gyroscope with long life time, and resistance to impact/vibration (accuracy must be the same as vibrating gyroscope).

In order to realize such a gyroscope, the authors consider an electro-conjugate fluid or ECF [5,6] in this study. The electro-conjugate fluid is a kind of smart fluid which generates a powerful jet flow (ECF jet) when subjected to high DC voltage. This means the electro-conjugate fluid could be used for fluid power systems without any bulky pumping systems. We introduce this attractive smart fluid in this study to gyroscopes and propose a novel *liquid rate gyroscope*.

This paper describes basics of electro-conjugate fluid, concept of our liquid rate gyroscope, prototype fabrication, experimental results, and conclusions.

II. BASICS OF ELECTRO-CONJUGATE FLUID

An electro-conjugate fluid or ECF is a dielectric fluid,

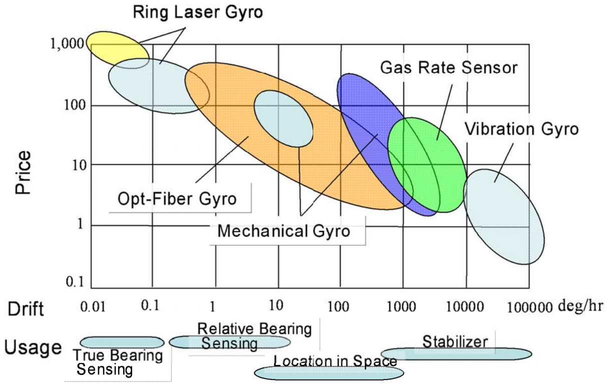

Fig. 1 Performance vs. price relation of gyroscope [1]

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which works here as a smart/functional fluid. Applying a high voltage of several kV between electrodes inserted into the fluid with an interelectrode gap of several hundred micrometers, we can observe a powerful jet flow - an ECF jet - between the electrodes (Fig. 2). The ECF jet may be observed especially under a non-uniform electric field produced by a rod-like electrode pair or a needle-ring electrode pair as in Fig. 2. Although a high voltage is necessary to generate the jet flow, the current is quite low at several μA.

We investigated about 50 dielectric fluids to determine whether each fluid showed the above-mentioned effect or not. The fluids plotted by white circles in Fig. 3 showed the effect in the experiments. As can be seen from the figure, the dielectric fluids showing the "ECF effect" are obviously plotted in a particular triangular area on the conductivity vs. viscosity relation (viscosity and conductivity are experimentally selected as parameters explaining the phenomenon) [6]. That is, plotted in this triangle is at least a necessary condition for fluids to show the ECF effect. From this result, the fluid satisfying this necessary condition is called an electro-conjugate fluid.

The mechanism of ECF effect has yet to be clarified, however, the effect itself is effective for engineering applications [7-12]. From our previous studies on electro-conjugate fluids, we clarified the following attractive features of electro-conjugate fluids:

- The ECF jet may be observed under an extremely non-uniform electric field.
- The ECF jet becomes more powerful as the electrode pair becomes compact, which means, the effect is suitable for micro fluid power systems.
- The fluid plotted closer to the origin of Fig. 3 shows a more powerful jet flow.
- When two or more fluids, each of them is not treated as an ECF, are mixed together to satisfy the above-mentioned necessary condition, the mixed fluid could possibly be treated as an ECF.

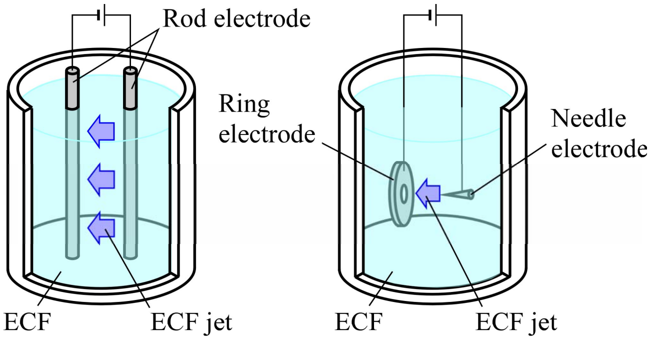


Fig. 2 Schematics of ECF jet

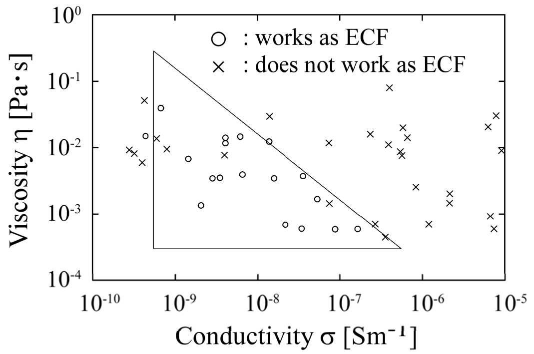
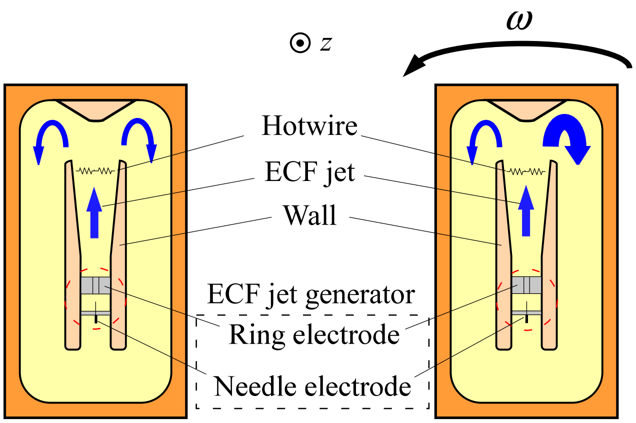


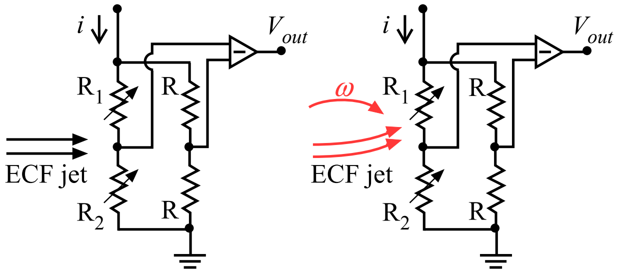
Fig. 3 ECF qualification

III. CONCEPT

Fig. 4 shows a schematic illustration and principle of a liquid rate gyroscope we propose in this study. The liquid rate gyroscope mainly consists of a jet generator (electrode pair), channel separation walls, and hotwires. Inside the gyroscope is filled with the electro-conjugate fluid. The jet generator has



(a) Schematic view



R_1, R_2: hotwire

(b) Sensing principle

Fig. 4 Concept of liquid rate gyroscope

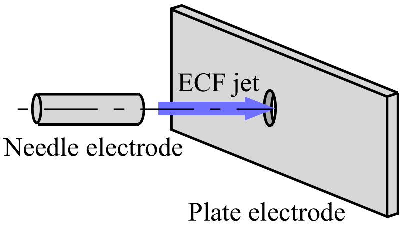


Fig. 5 Needle-plate electrode pair

a needle-plate electrode pair shown in Fig. 5. A small hole is located at the center of the plate electrode, and the ECF jet is generated from the needle tip through the hole when voltage is applied to the electrode pair.

In case the angular rate around the *z*-axis is applied to the liquid rate gyroscope, the flow inside is drifted due to Coriolis force resulting in making the resistance of two hotwires different. Then, the output from a hotwire bridge V_{out} changes.

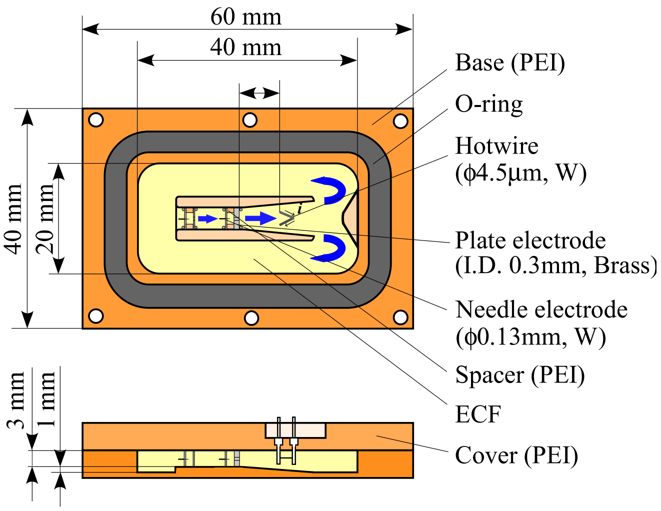
The above sensing principle has already conducted in a gas rate gyroscope [13], however, there needs a pumping system for making gas flow. Using the electro-conjugate fluid, we could remove the bulky pumping system from the gyroscope resulting in making it tiny and thin. In addition, using the liquid whose density is generally higher than that of gas is helpful for detecting the drift due to Coriolis force.

Our final goal is to develop a liquid rate gyroscope with dimension of 20mm × 30mm × t3mm.

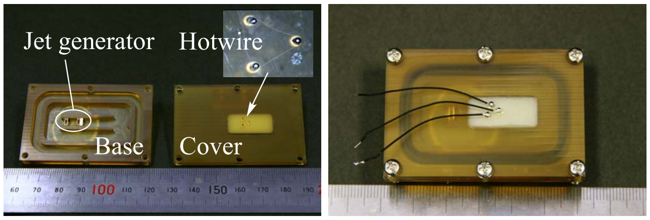
IV. PROTOTYPE

Fig. 6 is schematic illustration and actual view of a prototype we fabricated. The dimension of the prototype is 40mm × 60mm × t7mm, just for confirming our concept.

The prototype is mainly composed of a cover, a base having channel, and the electro-conjugate fluid (FF-1_{EHA2}, New Technology Management Co., Ltd., Japan, *cf.* Table 1). The cover has tungsten hotwires (ϕ4.5 μm) which are located in "V" shape as can be seen in the figure. The base has the jet generator. There are two needle-plate electrode pairs in order to accelerate the flow. Additionally, the second electrode pair has a thicker plate electrode than the first one. This is for making the straight stream. The detail of the electrode pair is shown in Fig. 7. The needle is made of tungsten and the plate is of brass, and their centers are corresponding.



(a) Schematic view



(b) Actual view

Fig. 6 Prototype

V. EXPERIMENTAL RESULTS

A. Experimental Setup

An experimental setup used in this study is shown in Fig. 8. The prototype, a high voltage power source (HV-10P, Matsusada Precision Co., Ltd., Japan), and a reference gyroscope with accuracy of <0.2% (AU4522, Tamagawa Seiki Co., Ltd., Japan) are located on a rotary table. The angular rate around the *z*-axis can be applied to the rotary table manually.

The input voltage to the jet generator is up to 6 kV with the high voltage power source, and the input current to the hotwires is 40 mA. The output from the hotwire is in the order of mV, so we amplify the signal at a signal converter which is also located on the rotary table. In addition, we could insert a first order low pass filter to the signal if necessary.

The output signal from the prototype is expected to be negative against the signal at 0 °/s when the rotary table rotates in clockwise (CW) with observing from the upper side of the table. On the other hand, it is expected positive when the table rotates in counter clockwise (CCW). This polarity is

Table 1 Physical property of FF-1_{EHA2}

Physical property	
Density@15°C [kg/m^3]	1.688e+3
Dynamic viscosity@30°C [m^2/s]	8.8e-6
Electric conductivity@1kV/mm [S/m]	5e-9
Boiling point@1atm [°C]	210

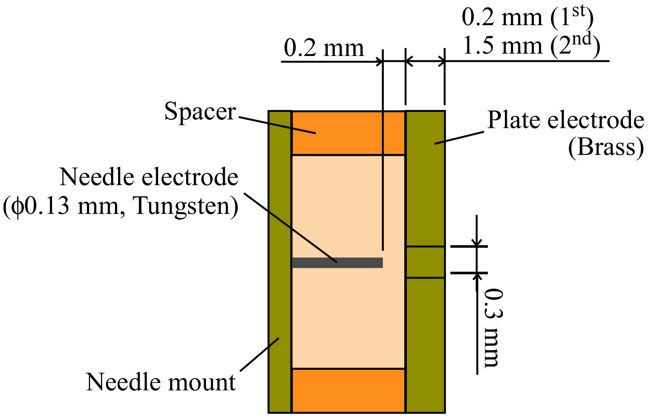
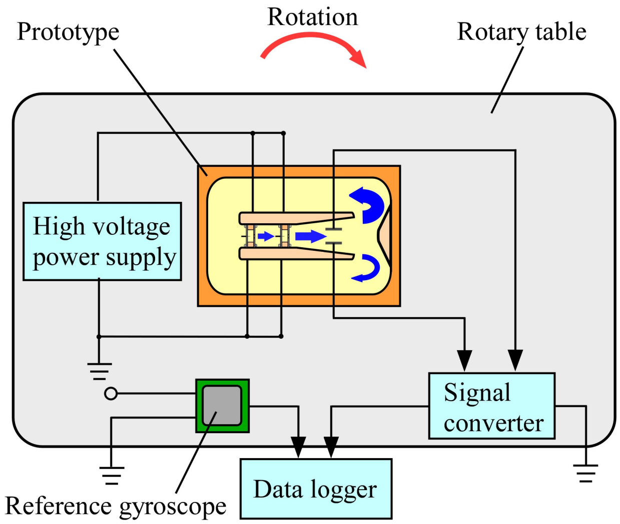
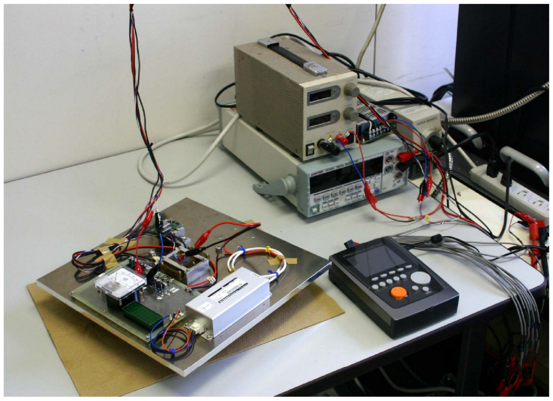


Fig. 7 Electrode pair



(a) Schematic view



(b) Actual view

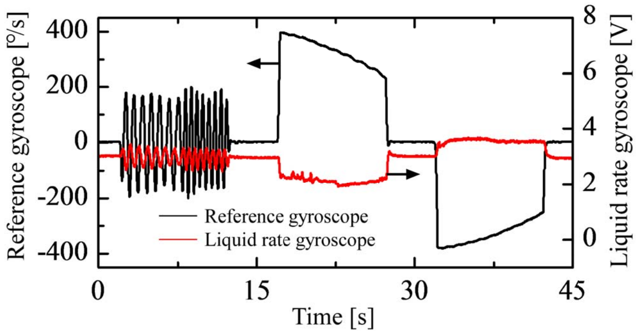
Fig. 8 Experimental setup

opposite from the output from the reference gyroscope due to the experimental setup.

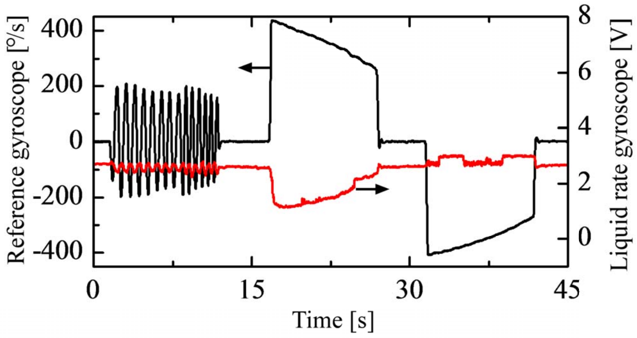
B. *Prototype Characteristics*

The ECF jet can be generated when the high voltage (~kV) is applied to the electrode pairs located in the base as mentioned above. It is interesting that the ECF jet can be observed when the needle is connected to the ground and the plate to the positive, and even when the needle is to the positive and the plate to the ground [14]. Hence we conduct the prototype evaluation with both conditions.

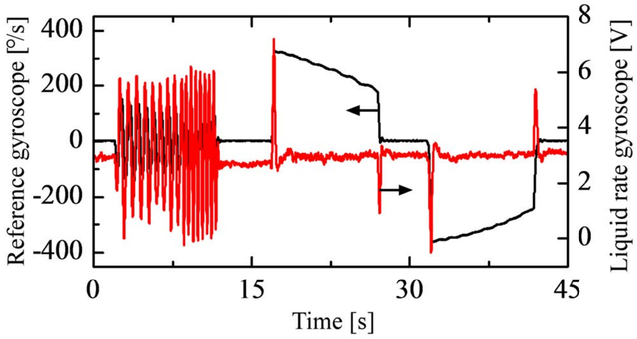
Fig. 9 shows the output voltage from the prototype and the reference gyroscope, where the gain at the signal converter is 550 and the cutoff frequency is 8.6 Hz. Fig. 9 (a) and (b) are the case when the needle is connected to the ground and the plate is to the positive. On the other hand, Fig. 9 (c) and (d) are when the needle is connected to the positive and the plate is to the ground. From Fig. 9, it is proved that when the needle is connected to the ground, the angular rate could be sensed with relatively low voltage, but the sensitivity against the angular rate is low. Meanwhile, when the needle is connected to the positive, the prototype could not sense the angular rate with relatively low voltage, however, with 5 kV, the output signal from the prototype successfully follows that from the reference gyroscope with high sensitivity.



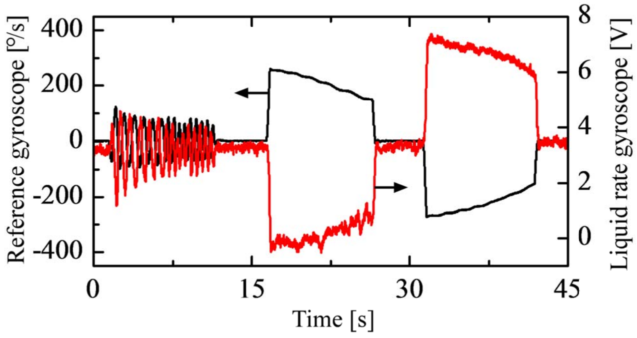
(a) 4.0 kV (Needle: GND, Plate: +)



(b) 5.0 kV (Needle: GND, Plate: +)



(c) 4.0 kV (Needle: +, Plate: GND)



(d) 5.0 kV (Needle: +, Plate: GND)

Fig. 9 Performance of prototype

The reason for the difference of sensitivity mentioned above might be the following. In case the plate electrode is

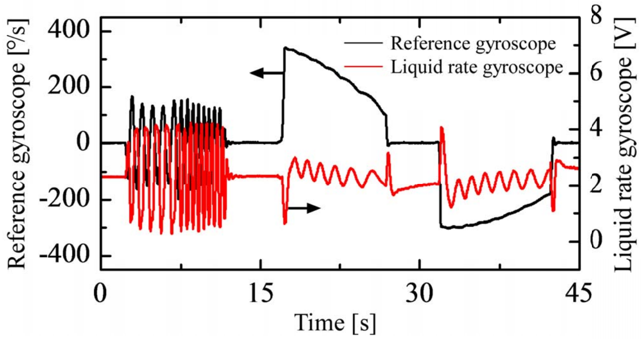


Fig. 10 Output from prototype when no voltage applied

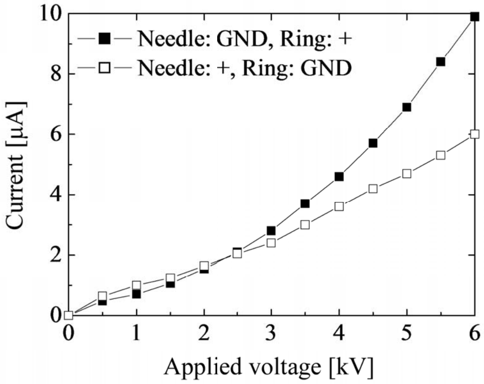


Fig. 11 Current during experiments

connected to the positive (~kV), the electric field distribution is pretty much affected by the electric potential of hotwires, which might cause the turbulence of jet flow at the downstream of jet generator. On the other hand, in case the plate electrode is connected to the ground, the electric potential of plate and hotwires are almost the same, which means the electric field distribution between the plate and hotwires scarcely affect on the jet flow.

In addition, Fig. 9 (c) seems showing the angular acceleration rather than angular rate just like the result when no voltage is applied to the prototype shown in Fig. 10. The reason for this might be as follows. With 4 kV (Fig. 9 (c)), the flow velocity of ECF jet is not high enough to obtain an appropriate drift due to Coriolis force making the resistance of two hotwires different. However, with 5 kV (Fig. 9 (d)) the flow velocity at around the hotwires is high enough to obtain an appropriate drift resulting in making the angular rate component dominant.

Fig. 11 shows the current during the experiments. In case the plate electrode is connected to the positive, the current increases quadratically against the applied voltage to the prototype. On the other hand, when the plate electrode is ground, it increases linearly. The power consumptions when 6 kV is applied are 60 mW (plate: +) and 36 mW (plate: GND), respectively.

C. Scale Factors

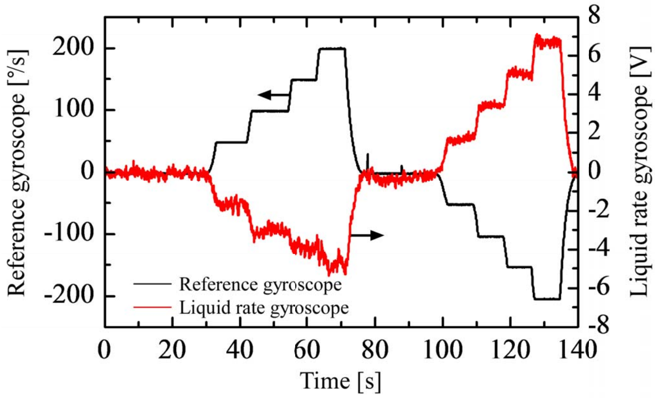


Fig. 12 Response against the step change of angular rate

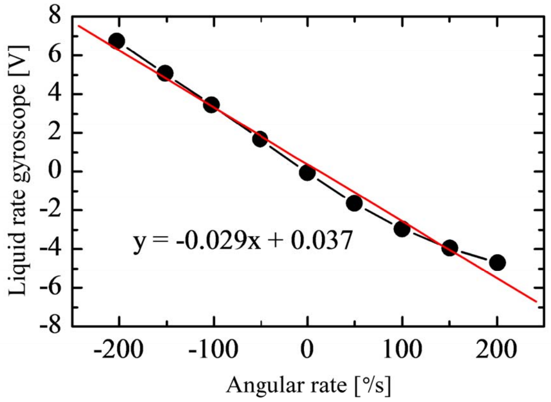


Fig. 13 Calculation of scale factor

In order to identify the scale factor of the prototype, we conducted an experiment with a rate table, which can precisely control the angular rate (C-181, Genisco Co., Ltd.). Namely, we changed the angular velocity of the rate table from 0 °/s to 200 °/s with every 50 °/s both in CW and in CCW. Note that the plate electrode is connected to the ground and the needle electrode to the positive.

The experimental result is shown in Fig. 12, where applied voltage, gain, and cutoff frequency are 4.5 kV, 1065, and 2.8 Hz, respectively. The output signal of the prototype with CW rotation is a bit noisy and seems to saturate when the angular velocity becomes high. On the other hand, the output signal with CCW rotation is almost proportional to the angular velocity applied. This may be because of the following reason. That is, the ECF jet does not perfectly flow straight, possibly out of alignment from the center, which means the ECF jet does not flow at the center of hotwires. If this the case, there could be a possible difference of sensitivity between CW and CCW rotation, and the output signal from the prototype for CW could be saturated with relatively higher angular velocity because the ECF jet possibly be out of the hotwire. In addition, the output ranges of prototype in Fig. 9 and Fig. 12 are different also because of the flow being out of alignment from the hotwire center.

Fig. 13 is a relation between the angular rate and the output signal from the prototype. The approximated curve calculated using the least-square technique is shown in the figure as well. The gradient of the approximated curve, generally called “scale factor” for gyroscope, is -29 mV/(°/s). However, it is obvious the relation between angular rate and the output signal from the prototype is nonlinear. This might be because of the initial drift of the ECF jet due to the hand assembling error. This could be easily improved when the assembling process is improved. Then, the prototype could measure at least ±200 °/s with high linearity.

VI. CONCLUSIONS

We proposed in this study a novel liquid rate gyroscope which uses an attractive smart fluid, electro-conjugate fluid. The basic sensing principle is based on that of the gas rate gyroscope, however, the liquid rate gyroscope does not require a bulky pumping system inside. This means the proposed gyroscope could be extremely compact in size and thin. The experimental results of the prototype confirm the operating principle of the liquid rate gyroscope and show the possibility of the liquid rate gyroscope.

Our future study focuses on an optimum design of the channel, jet generator, and hotwires, followed by realizing our final goal gyroscope with dimension of 20mm × 30mm × t3mm.

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