

# Tri-axis Convective Accelerometer with Closed-Loop Heat Source

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## Abstract

In this paper, we report the details and findings of a study on tri-axis convective accelerometer, which is designed with the closed-loop type heat source and thermal sensing hotwire elements. The closed-loop heat source enhances the convective flow to the central part where a hotwire is placed to measure the vertical component of acceleration. The simulation was conducted using numerical analysis, and the device was prototyped by additive manufacturing. The device, functioning as a tilt sensor and an accelerometer, was tested up to acceleration of 20g. The experiments were successfully conducted and the experimental results agreed reasonably with those obtained by numerical analysis. The results demonstrated that the closed-loop heat source could reduce the cross effect between the acceleration components. The scale factor and cross-sensitivity had the values of 0.26  $\mu\text{V/g}$  and 1.2%, respectively. The cross-sensitivity and the effects of heating power were also investigated in this study.

**Keywords:** convective accelerometer, tri-axis, closed-loop heater, hotwire, OpenFOAM.

## I. INTRODUCTION

Recently, micromachined accelerometers have undergone rapid development, and are widely used in various applications. Solid-state accelerometers have high performance, but also possess some setbacks. They are more fragile, fabricated by complicated process, and need complex packaging in order to remove the squeeze film effect between the proof mass and the accelerometer structure [1]. In Refs. [2], [3], the authors presented the first accelerometers without the proof mass, working under the principles of thermal convection heat transfer. Micro thermal convective accelerometers utilizing thermal bubble have been studied over the last two decades [4]. The operation of this type of sensor is based on the movement of a hot tiny air bubble generated from a heater. From then on, research has been carried out with focus on improving the sensor performance by optimizing the heat transfer [5–25], signal conditioning [26–28], behavior modelling [29–32], or fabrication process [33–35].

Most of the developed thermal accelerometers can measure only two components of the in-plane acceleration. Measuring the out-of-plane acceleration is more challenging because the principle of this kind of sensors is based on natural convective flow, which always aligns with the vertical gravity. Thus, the vertical acceleration requires an out-of-plane structure and has small sensitivity.

Leung et al. reported one of the first tri-axis accelerometers. The device is made by polyimide and assisted by wire bonding process for out-of-plane structure [36]. In Ref. [37], the accelerometer is made by micromachining process utilizing polysilicon as the sacrificed layer and polyimide as the structural layer. To launch the device, the

1 structures firstly need to be locked between each other and anchored to the substrate. This device allows  
2 obtaining the Z sensitivity of 25  $\mu\text{V/g}$ .

3 In the works published by Rocha and Silva [38–41], a polymeric three-axis device was fabricated by  
4 conventional micromachining and injection molding. The heating and the temperature sensing structures, made  
5 of aluminum, were patterned on a flexible polymeric membrane. The membrane was then folded so that parts of  
6 the membrane consisting of z-sensors were placed above and under the central part, which consisted of the heater  
7 and the in-plane x-y sensors. The device with performance of approximately 2.2  $\mu\text{V/g}$  was packaged using  
8 polystyrene parts made by injection molding, and was hermetically sealed.

9 The Z-axis acceleration detected by in-plane structure was reported by Maily et al. in [42,43] using integrated  
10 CMOS (complementary metal–oxide–semiconductor). This device measures out-of-plane acceleration by using  
11 common mode of the in-plane structure. MEMSIC Inc. has also claimed a three-axis device. However, the principle  
12 is not disclosed, although it is said that the device uses the common mode of the electric bridge [4,44]. Another  
13 principle for the triple-axis accelerometer has been proposed in [45] but without further discussion about  
14 efficiency. In Refs. [46,47], the design of three-axis thermal accelerometer using segmented circular heater was  
15 mentioned. Using numerical simulation, Ogami et al. reported that the sensor could reliably determine a vast  
16 range of vertical acceleration, specifically,  $\pm 10,000$  g [47]. However, the experimental details were omitted.

17 As already mentioned above, it is difficult to detect the acceleration in the z-direction accurately. For measuring  
18 this acceleration, the temperature detecting components need to be arranged above and below the heater. When  
19 acceleration occurs, the detected temperatures change, but only by small amount. It has been found that the Z-  
20 axis detection accelerometer has a close relation with the natural convection of the flow inside a cavity heated  
21 from below [48–53]. In recent years, many researchers have found that boundary conditions [48,49] and heater  
22 geometry [50,51] have substantial impact on the pattern of these convective flows. Because of the temperature  
23 distribution, the local heating of the quiescent air over the heater surface produces density gradient directed  
24 toward the decrease in the medium temperature, and convective flow occurs in the form of thermal plume when  
25 the buoyancy exceeds the viscous friction [53]. For a single local heater under heating conditions, the hot air rises  
26 upwards along the vertical axis going through the heater. Therefore, the convective flow has high stability in the  
27 plane of the heater, but is less stable in the vertical direction [54]. These characteristics of flow from the plate-  
28 type heater usually employed in convective accelerometer reduce the sensitivity of the vertical acceleration  
29 sensing. Another setback is the interference between the measured acceleration components. Because of  
30 arrangement of the temperature detectors, when the acceleration in one direction causes a change in the  
31 corresponding temperature, it also affects the temperature elements of the remaining directions and distinctly  
32 lowers the measurement accuracy.

33 In this paper, we demonstrate a novel approach to develop a tri-axis convective accelerometer with reduced  
34 cross effect between the vertical and horizontal acceleration. This design, inspired by the numerical simulation in  
35 [55], involves development of accelerometer utilizing the ring-type heat source. The designed device consists of a  
36 closed-loop heater with hotwires placed both inside and outside of the heater. The closed-loop heater enhances  
37 the convective flow to the central part, where the temperature detector is positioned to measure the vertical  
38 component of acceleration. Outside the loop, other hotwires detect the horizontal components. The  
39 characteristics of the sensor are experimentally validated by tilting the device and by applying linear acceleration.  
40 The principles of the device, numerical simulation, and the effect of several governing parameters are also  
41 explored to investigate the reliability of the device.

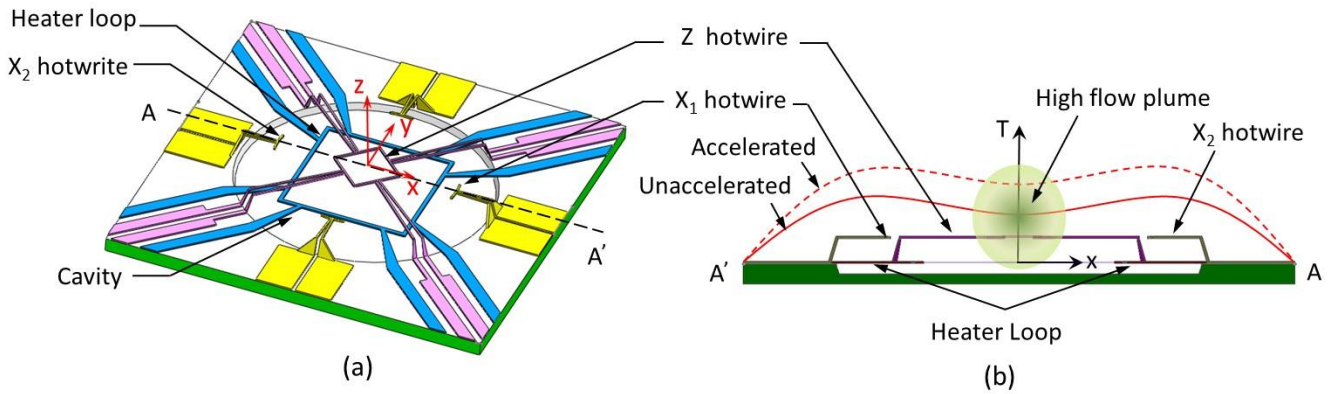
## 42 II. WORKING PRINCIPLE

43 In general, the principle of acceleration sensing can be summarized as follow. The sensing chip, formed by one  
44 heater placed at the center and surrounded by hotwires (temperature detector), is packed in an airtight chamber.  
45 At the initial state, the heater creates a symmetrical temperature profile inside the chamber. When the device is  
46 subjected to acceleration, the locally heated air moves in the direction of this applied acceleration, causing

1 temperature distortions  $\Delta T$ , which are then sensed by the hotwires. For horizontal measurement  $a_x$  or  $a_y$ , the  
 2 output of sensor is given by  $\Delta T_x$  or  $\Delta T_y$  at the X or Y hotwires, respectively (Fig. 1a). For vertical measurement,  
 3 the output is determined by the output of  $\Delta T_z$  at the Z hotwire.

4 In most of the conventional accelerometers reported in the first section, the heater is suspended at the center and the hotwires are located around the heater. Consequently, the change in temperature caused by the variation  
 5 of the vertical acceleration is low in comparison with that caused by the variation of the horizontal acceleration,  
 6 and the cross-sensitivities between these measurements are high. In our design shown in Fig. 1, the heater forms  
 7 a full loop and the hotwires are located both inside and outside of the heater. The plane of the hotwires has a  
 8 small elevation from the heater plane for vertical and horizontal measurements.  
 9

10 In the closed-loop heater, the primary flow concentrates strongly within the central portion even if heat is not  
 11 supplied there [56,57]. The high temperature air is concentrated in the central part, except in a very thin layer  
 12 above the heat source. As this concentrated hot air has high buoyancy, the temperature varies with the vertical  
 13 acceleration  $a_z$ . This increases the sensitivity of the vertical measurement significantly and reduces the cross-effect  
 14 of horizontal acceleration, which is one of the limits of the conventional design.  
 15



16  
 17 **Figure 1.** (a) Configuration of the sensor with the radius of the cavity of 0.75 mm. (b) Position of the hotwires in  
 18 the cross section along the A–A' axis and principle to measure the vertical acceleration. The hotwires are on the  
 19 same plane, and the heater is underneath. The Z hotwire is above the central portion of the heater to utilize  
 20 convectively heated air from the ring-type heater.

### 21 III. SIMULATION AND DESIGN

22 The thermofluidic phenomena in the sensor are described by the temperature dependence of the fluid density.  
 23 This process is governed by the laws of conservation of mass, momentum, and energy for compressible fluids and  
 24 is expressed as follows:

$$25 \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

$$26 \quad \frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{u}) + \rho \vec{a} \quad (2)$$

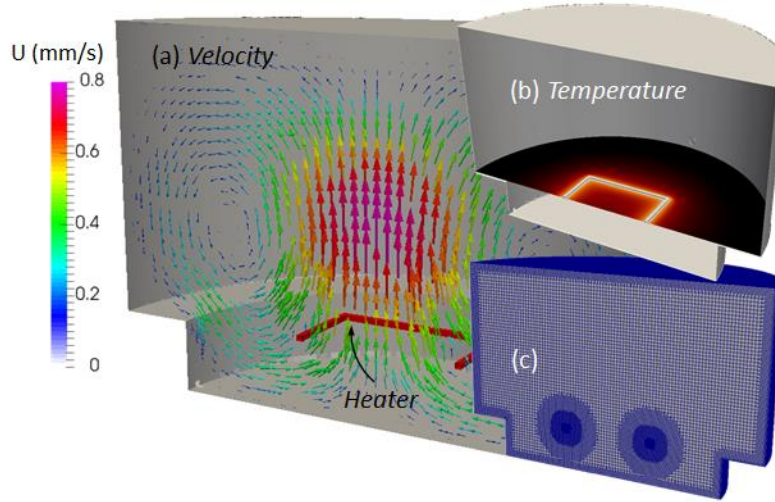
$$27 \quad \frac{\partial \rho c_p T}{\partial t} + \vec{u} \cdot \nabla \rho c_p T = \nabla \cdot (\lambda \nabla T) \quad (3)$$

28 where  $\vec{u}$  and  $p$  are velocity and pressure of the fluid flow, respectively. Similarly,  $\rho$ ,  $c_p$ ,  $\mu$  and  $\lambda$  are density,  
 29 specific heat, viscosity, and thermal conductivity of the fluid, respectively. The term  $\vec{a}$  is the acceleration vector,  
 30 while  $\rho \vec{a}$  represents the momentum source because of the change in fluid density. As air is the medium in this  
 31 study, the ideal gas law for compressible flows is valid. This can be stated as

$$p = \rho RT/M_w \quad (4)$$

where  $R$  is the universal gas constant and  $M_w$  is the molecular weight of the gas.

The sensor is decomposed into a hexagonal mesh clustered near the heater and walls to capture the steep change of temperature. The flow parameters on this mesh are then obtained by the computational fluid dynamics package OpenFOAM, which uses the finite volume method to discretize the governing equations. The simulation model is presented in Fig. 2.

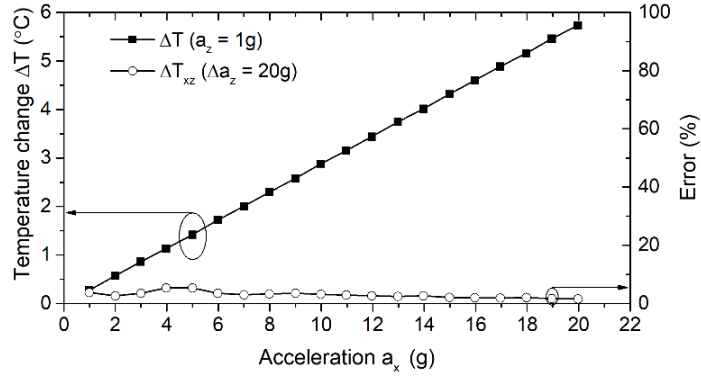


**Figure 2.** (a, b) Simulation results and (c) meshing of the model. Simulation shows that (a) flow velocity concentrates within the region above the center of ring-type heater while (b) the temperature is highest at the thin layer around the heat source.

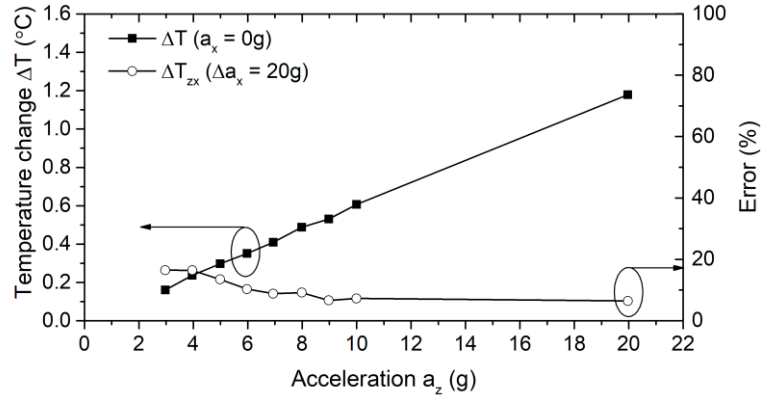
From the simulation, it can be seen that the high temperature air is formed in the central portion above the heater except a thin layer around the heat source and the peak of temperature is distributed toward the center of the rim. For the velocity, the main part of the convection is strongly concentrated in the central part of the heater where no heat is supplied at the bottom. By placing a sensing element in this region, the specific character of the closed-loop type heater allows efficient measurement of the vertical acceleration and reduces the cross-effect of the horizontal acceleration. All of these phenomena will be discussed in the following paragraphs.

Considering the earth's gravity  $g$ , we discuss the sensor performance by comparing the initial state  $a(0, 0, 1 \text{ g})$  and the accelerated state  $a(a_x, a_y, a_z - 1 \text{ g})$ . Because of the equivalency between the  $x$  and  $y$  components, only the measurements of  $x$  and  $z$  components of acceleration are taken into consideration. The sensitivity of the sensor can be determined from  $\Delta T_x$  and  $\Delta T_z$ , which are the temperature changes at the X hotwire and Z hotwire when the accelerations are applied on the X and Z axes, respectively. The cross-effect between the vertical and horizontal measurements is determined by  $\Delta T_{xz}$  on the X hotwire under the effects of  $a_z$  and by  $\Delta T_{zx}$  on Z hotwire under the effects of  $a_x$ . In the simulation, the sensitivity and cross-effect are examined by simultaneously applying  $a_x$  and  $a_z$ .

Figure 3 shows that the variation in temperature differences on the X hotwire ( $\Delta T_x$ ) with  $a_x$ , ranging from 0 g – 20 g, for the cases of  $a_z = 1 \text{ g}$  and  $a_z = 21 \text{ g}$ . It is observed that  $\Delta T_x$  varies linearly with  $a_x$  with the sensitivity  $\Delta T_x/a_x \sim 0.29 \text{ }^\circ\text{C/g}$ . The effect of  $a_z$  on  $\Delta T_x$ , error  $\Delta T_{xz}(\%) = (\Delta T_{x,az=21g} - \Delta T_{x,az=1g})/\Delta T_{x,az=21g}$ , is within 5% (in comparison with  $\Delta T_x$  at  $a_z = 1 \text{ g}$ ).



1 **Figure 3.** Variation of the temperature difference between the hotwires  $X_1$  and  $X_2$  for  $a_x$  ranging from 1 to 20 g.  
 2 The error represents the percentage of temperature change  $\Delta T_{xz}$  between  $a_z = 21$  g and  $a_z = 1$  g.  
 3  
 4



5 **Figure 4.** Variation of the temperature difference between the accelerated state and the normal state at the Z  
 6 detector, with  $a_z$  ranging from 1 to 20 g. The error represents the percentage of temperature change  $\Delta T_{zx}$   
 7 between  $a_x = 20$  g and  $a_x = 0$  g.  
 8

9 Similarly, for cases of  $a_x = 0$  g and  $a_x = 20$  g, Fig. 4 shows the change of temperature on Z hotwire ( $\Delta T_z$ ) with  
 10  $a_z$ . Again,  $\Delta T_z$  increases linearly with  $a_z$  up to  $a_z = 20$  g with the sensitivity  $\Delta T_z/a_z \sim 0.059$  °C/g.

11 With  $\alpha$  as the temperature coefficient of resistance of the hotwire material, the conversion between the  
 12 hotwire temperature and its resistance can be expressed as:

$$R = R_{ref}(1 + \alpha \Delta T) \quad (5)$$

14 where  $\Delta T = T - T_{ref}$ ,  $R$ , and  $R_{ref}$  are the resistances of the hotwire at temperature  $T$  and  $T_{ref}$ , respectively. **In the**  
 15 **experiment, the resistance is measured by supplying a constant direct current (d.c) and monitoring its voltage.**

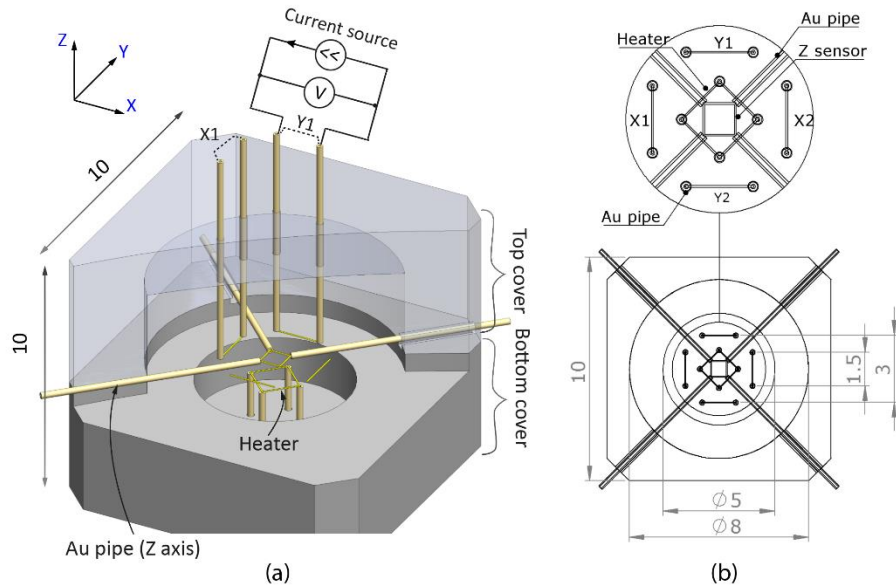
#### 16 IV. PROTOTYPE AND EXPERIMENTAL SETUP

17 The sensor designed for the experiment consisted of top and bottom parts (Fig. 5a), which were connected as  
 18 the male-female components of an assembly, to prevent the leakage of the air, which was used as the working  
 19 medium in this device. The top view showing the layout of the hotwires and the heater is presented in Fig. 5b. **The**  
 20 **dimensions 10 mm × 10 mm × 8 mm (width × length × thickness) of the fabricated device are chosen based on**  
 21 **several designs available for the dual axis convective accelerometer and the consideration of our available facilities**  
 22 **[12].** The hotwire and heater were made of tungsten wire with diameter 10  $\mu\text{m}$ . To place these elements at the  
 23 desired positions, hollow capillary gold (Au) pipes 200  $\mu\text{m}$  × 25  $\mu\text{m}$  (outer diameter × thickness) were used as the

1 lead pins. The capillaries were assembled with the packing and fixed with epoxy glue; the tungsten wires were  
 2 then inserted through those capillaries and connected with each other. Together they created floating structures.  
 3 This method allowed the construction of the sensor with high precision and cost-effectiveness.

4 Figure 6a shows the prototype made of polypropylene. The heaters were supported by four Au pipes and were  
 5 integrated with the bottom part. The hotwires were connected to the top part, where each X and Y hotwire was  
 6 supported by two Au pipes at its end. The Z sensor and the heater were supported by four Au capillaries to form  
 7 a loop-like resistor. The positioning of the capillaries was assisted by assembly jig (not shown). After the hotwires  
 8 were connected and the electrical connections were confirmed, the top and bottom part were assembled and  
 9 sealed by epoxy at the standard room condition (22–25 °C, 60% RH).

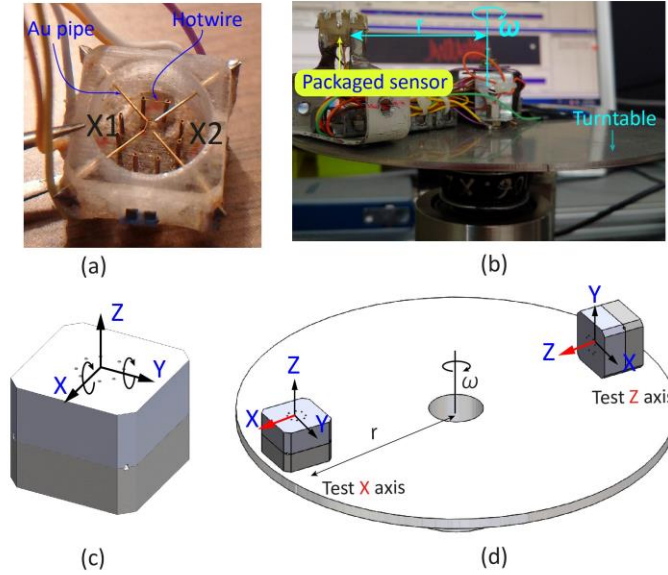
10 The temperature coefficient of resistance was measured as  $\alpha \approx 4500 \text{ ppm}/^\circ\text{C}$  using the temperature controlled  
 11 chamber (Espec SH-222). **Without conditioning circuit, the measurement of the hotwire/heater was conducted by**  
 12 **four-point probe measuring technique. A constant electric current was applied by the TEXIO DC power source**  
 13 **(PW18-1.8AQ) and the output voltage was continuously recorded by a computer via NI (National Instrument Ltd.,)**  
 14 **signal express data logging interface connected to the NI-9234 data acquisition device with the sampling rate of**  
 15 **25.6 kHz.** At the initial state, the measured resistance values of the hotwires X, Y, Z, and heater were 1.7, 1.9, 1.2,  
 16 and 1.3  $\Omega$ , respectively.



**Figure 5.** (a) Schematic view of the designed prototype with the cut-view showing the lead pin (made by Au capillary) and hotwires. (b) Dimensions of the central regions.

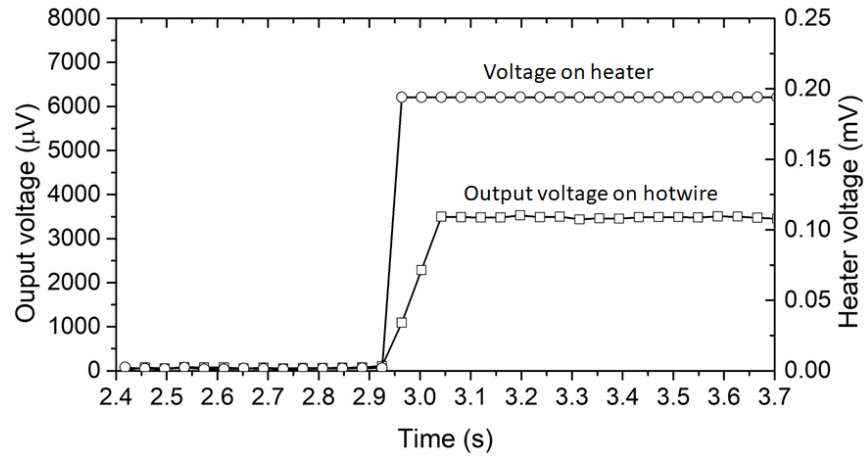
17 The sensing performance of the device was checked by the tilting test and linear acceleration test. For the tilting  
 18 test, the device was attached to a circular disc placed vertically and tilted around the X and Y axes, while the  
 19 voltages on the hotwires X, Y and Z were read out (see Fig. 6c).

20 The linear acceleration sensing was tested by placing the device at the edge of a self-developed turntable (see  
 21 Fig. 6b), whose angular velocity was controlled by a direct current motor with integrated encoder (Tsukasa Electric  
 22 Ltd.). When the turntable rotated, the centrifugal acceleration acted to the device was  $a = (2\pi n)^2 r_t$ , with  $n$  and  
 23  $r_t = 4.5 \text{ cm}$  were the angular speed and radius of the turntable, respectively. The on-chip circuit was connected  
 24 via the slip-ring to the off-chip circuit to transfer the signals while the turntable rotated. The table revolution had  
 25 a maximum value of 700 rpm during the experiment, and its rotation was recorded by the PIC18F4520  
 26 microcontroller via encoder motor. **The output voltage was extracted one minute after the turntable reached the**  
 27 **rotation speed to ensure that the centrifugal acceleration and the flow inside device were stable.**



**Figure 6.** (a) Close-up view of the prototype showing hotwires and Au pipes, (b) package device with holder placed on the turntable, (c) tilting test: experiment for determining tilting along the X and Y axes, and (d) linear acceleration test: experiment for determining centrifugal acceleration along the X and Z axes.

1 The start-up time of the device was acquired from the transient time of the output voltage on the hotwire X  
 2 (plotted in Fig. 7). It was found that the start-up time was around 100 ms for the X axis, which was located 1.0 mm  
 3 from the heater, with the applied current of heater  $I_{heater} = 110\text{mA}$  ( $V_{heater} = 0.177\text{V}$ ). This start-up time,  
 4 including the time delay in the electric circuit, also represented the time scale for heat transfer from the heater  
 5 to the hotwire until the temperature in the sensor chamber became stable.  
 6



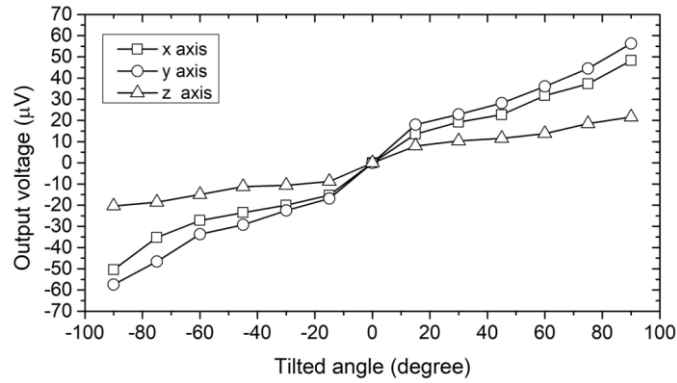
**Figure 7.** Experimental result for the transient measurements of voltages on the heater and the hotwire X.

## V. EXPERIMENTAL RESULT

### 1. Tilting sensitivity of X and Y axes

9 For the tilting test, the outputs of hotwires were monitored while the sensor was being rotated to ensure that  
 10 the corresponding hotwire moved from underneath the heater to the top of the heater. In Fig. 8, they are the  
 11 tilted angles  $-90^\circ$  and  $+90^\circ$ . The output voltage on X and Y hotwires are recorded when the sensor is tilted around

1 the Y axis and the X axis, respectively. The output on the Z axis is recorded when the sensor is tilted around the X  
 2 axis (see Fig. 6c).

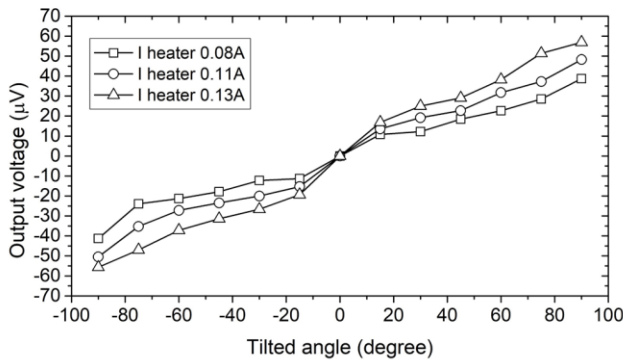


**Figure 8.** Output voltages on the X, Y, and Z hotwires while tilting around the X and Y axes.

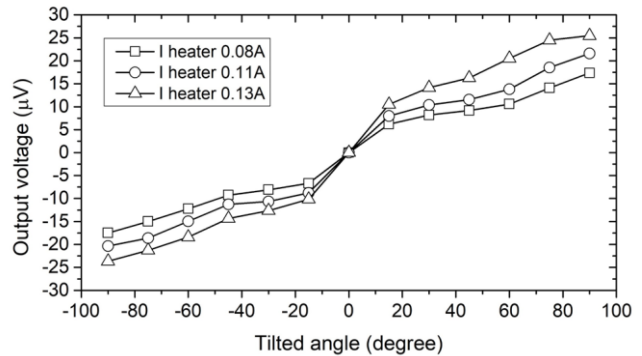
3 The heater is heated with a constant current of 110 mA. The change in the heater resistance allows us to  
 4 estimate the temperature of the heater by using the relation  $\alpha\Delta T = \Delta R/R$ , and its value is found to be  
 5 approximately 70 °C. From Fig. 8, the sensitivities on the X axis and the Y axis are averaged as  $V_{xx} = 0.62 \mu V/^\circ$  and  
 6  $V_{yy} = 0.53 \mu V/^\circ$ . The input of the Z hotwire while rotating around the X axis is  $V_{zz} = 0.23 \mu V/^\circ$ , which is of the  
 7 same order as those of the X and Y axes. With the measured resistance at initial state of  $R_x/R_z = 1.7$  (see part IV),  
 8 the change in temperature in the hotwires X and Z is approximated as  $\Delta T_x/\Delta T_z = (V_{xx}/V_{zz})/(R_x/R_z)$ . For the  
 9 result in Fig. 8, the temperature  $\Delta T_x$  is 1.9 times higher than  $\Delta T_z$ . This value relatively agrees with the simulation  
 10 results presented in Figs. 2 and 3.

11

12 **2. Effect of supply current on the heater**



**Figure 9.** Effect of the heating current to the output voltage for the X axis sensing



**Figure 10.** Effect of heating current to the output voltage for the Z axis sensing

13 The sensing ability of devices can be enhanced by increasing the temperature of the heater, since the  
 14 temperature of the heater is directly related to how the medium can move inside the device [12,43]. A low  
 15 temperature heater will significantly restrain the flow and degrade the sensor performance. The experiment was  
 16 repeated in this study where the heater was subjected to three currents  $I_h = 80 \text{ mA}$ ,  $110 \text{ mA}$ , and  $130 \text{ mA}$ . The  
 17 obtained results are shown in Figs. 9 and 10. It can be seen that when the current increases from 80 mA to 130  
 18 mA, the output increases by 127% of the magnitude for the X axis and by 146% for the Z axis. Therefore, the output  
 19 voltages at the hotwires can be adjusted by the heater current, which can be used to accelerate the experiment.

20 **3. Sensing linear acceleration**

21 For the linear acceleration test, the output voltage is monitored while the sensor is placed at the edge of the  
 22 turntable rotating at 135 rpm (centrifugal acceleration 0.89 g) and the heater is heated with a current  $I_h = 110 \text{ mA}$ .

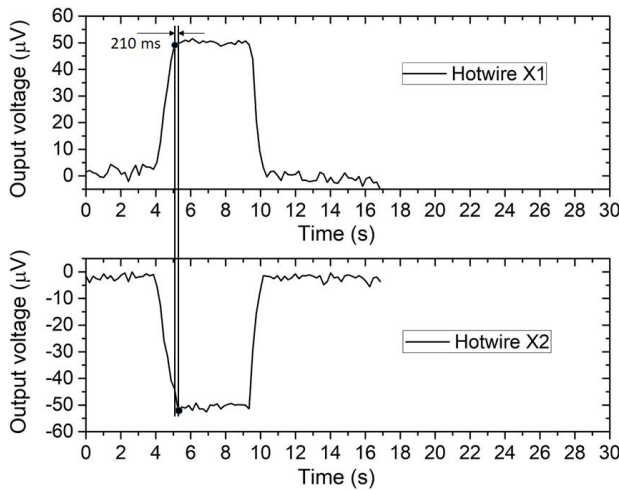


1 Figures 11 and 12 show the transient output voltage of the hotwires  $X_1$  and  $X_2$  when the acceleration is along the X  
 2 and Z axes, respectively (see experimental setup in Fig. 6d). The changes between these two hotwires are almost  
 3 similar in time, with a mismatch of only 210 ms at the left-peak slope. In Fig. 11, the two hotwires change their  
 4 voltages opposite to each other, whereas in Fig. 12, their voltages change similarly, indicating that the heated air  
 5 region changes the temperature of the X hotwire asymmetrically and symmetrically under the x and z applied  
 6 accelerations, respectively.

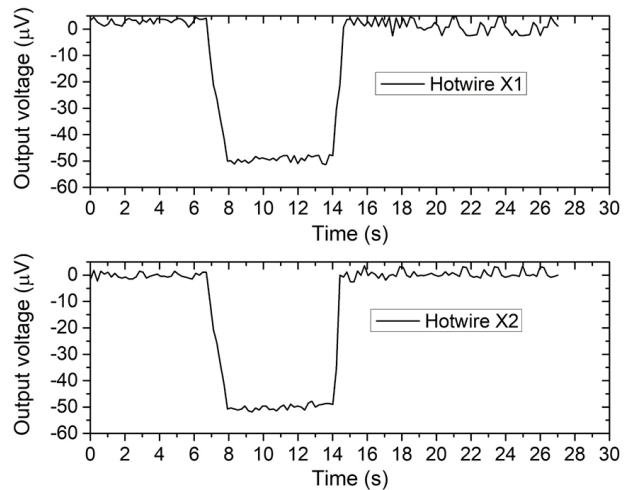
7 The average noises are approximately  $5 \mu\text{V}$ , significantly larger than the resolution of the 24-bit measuring  
 8 device NI-9234 data acquisition. Therefore, the resolution of the sensor can be calculated as the signal-to-noise  
 9 ratio, as shown in Figs. 11 and 12, and it is equivalent to  $0.09\text{g}$ . The results also show very small drift evolution,  
 10 nevertheless, the long-term drift evolution was not thoroughly tested for our device.

11 As the magnitudes of the voltages are almost the same in each case (Figs. 11 and 12), the effect of the Z  
 12 acceleration can be cancelled out easily by means of a conventional electric circuit such as by forming half  
 13 Wheatstone bridge by the pair of X hotwires. This kind of circuit is common in use in various sensing techniques, as  
 14 reported in numerous literature [37],[39].

15



**Figure 11.** Transient response of the hotwires X with acceleration applied along the X axis.



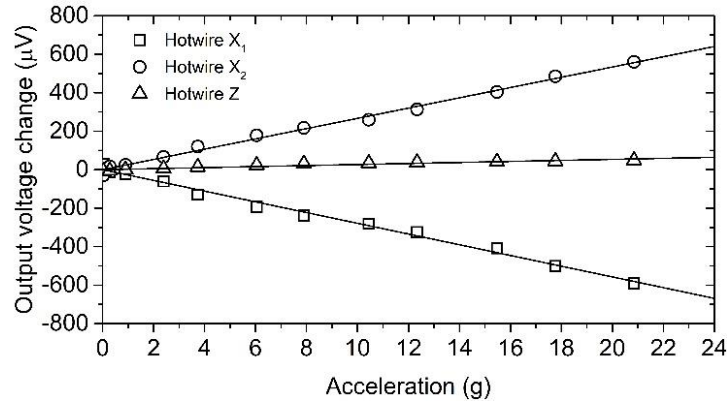
**Figure 12.** Transient response of the hotwires X with acceleration applied along the Z axis

16

17 Figure 13 shows the variation of the output voltage on the hotwires X with respect to the centrifugal  
 18 acceleration applied to the X axis by the turntable (see Fig. 6d). The two X hotwires change their resistance  
 19 opposingly when the scale factors of the hotwires  $X_1$  and  $X_2$  are  $SF_{xx1} = -27.8 \mu\text{V/g}$  and  $SF_{xx2} = +26.7 \mu\text{V/g}$ , with the  
 20 non-linearities (the ratio of output variation to maximum output full scale) of these output voltages being 2.7%  
 21 and 2.2%, respectively.

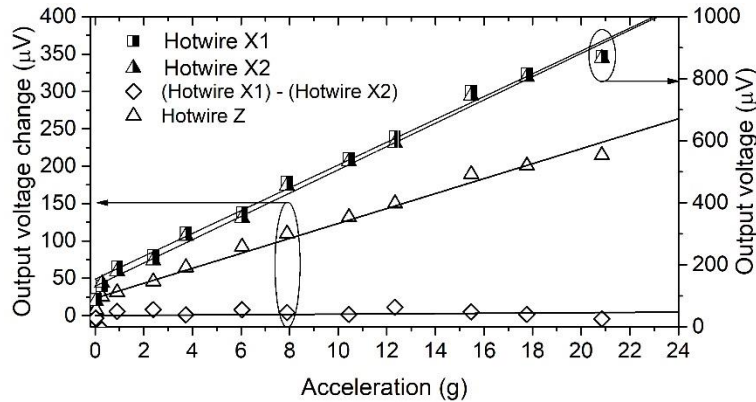
22 The results depict that the output voltage changes linearly with the change of the rotation speed until the  
 23 centrifugal acceleration reaches  $21\text{g}$ . Meanwhile, the output voltage of the Z hotwire is significantly lower with  
 24 the scale factor of  $SF_{zx} = 2.2 \mu\text{V/g}$ . These results indicate that the cross-sensitivity between the two axes is less  
 25 than 8%, thereby closely matching with the simulation.

26



**Figure 13.** Output of the X axis and Z axis when the centrifugal acceleration is applied along the X axis by the turntable (rotating speed from 25 rpm to 700 rpm).

Similarly, Fig. 14 shows the output voltages of the hotwires in the X and Z axes while the centrifugal acceleration is applied to the Z axis (see the experimental setup in Fig. 6d). The two X hotwires are parallel with the plane of the turntable and should have similar response to the acceleration. This is confirmed by the data below where the two hotwires respond similarly. The scale factors of the X hotwire under Z acceleration are  $SF_{xz1} = 37.7 \mu\text{V/g}$  and  $SF_{xz2} = 37.5 \mu\text{V/g}$ . If the X hotwires are conventionally connected by the half-bridge circuit, the total output of the X axis will be cancelled out (Fig. 14). In the meantime, the scale factor and the nonlinearity of Z hotwire under the Z acceleration are  $SF_{zz} = 10.2 \mu\text{V/g}$  and 3.8%, respectively.



**Figure 14.** Output of the Z axis and the X axis when the centrifugal acceleration is applied along the Z axis by the turntable (rotating speed is from 25 rpm to 700 rpm and the current at the heater is  $I_h = 110 \text{ mA}$ )

Overall, the sensing performance of the present device is in the same order as the values in recent publications. In the simulation, the relative sensitivity of  $\Delta T_z / \Delta T_x$  is in the same order with simulated result reported by other research group [58]. However, the sensing performance of the vertical acceleration of the presented device is less significantly affected by the horizontal acceleration. The performance of several published tri-axis convective accelerometers is summarized in Tab. 1. With these performing characteristic, the presented device and those sensors are in the same grade as classified in [59].

Table 1. Characteristics of some published tri-axis convective accelerometer

	X	Y	Z	$V_{zx}$ (effect of $a_x$ on the Z axis)
Bahari and Leung [36,37]	66 $\mu\text{V/g}$	64 $\mu\text{V/g}$	25 $\mu\text{V/g}$	84%
Rocha and Silva et al [38,39]	8.4 $\mu\text{V/g}$	7.9 $\mu\text{V/g}$	2.2 $\mu\text{V/g}$	Not reported
Maily and Nguyen et al [42,43]	7.2 mV/g	10 mV/g	0.4 mV/g	Not reported
This work	27.8 $\mu\text{V/g}$ (X)		10.2 $\mu\text{V/g}$	8%

1 It is worth noting that using the turntable to generate linear acceleration also induces Coriolis acceleration  
2 to the moving convective flow inside the device. The contribution of the Coriolis acceleration, however, is  
3 insignificant because the gravity driven flow has limited velocity in tiny confined space. The Coriolis acceleration  
4 is calculated as  $2\vec{\omega} \times \vec{U}$  [60–64], where  $U$  is the velocity of flow inside the device and is estimated by simulation  
5 in order of millimeters per second (please refer to Fig. 2). The ratio of the centrifugal acceleration to the Coriolis  
6 acceleration,  $\omega r_t/2U$ , is therefore three orders of magnitude. **Another concern in our experimental work is the  
7 output of tilting performance, which was not as linear as predicted by the simulation. The reasons are probably  
8 (i) the imperfection of the assembly process and (ii) the shape of the heater. While the circular-loop is ideal for  
9 the symmetry of device, it was not implemented for experimental measurement. We have confirmed by the  
10 simulation that the effect of the closed-loop heat source is more pronounced in the circular shape, however, the  
11 square shape heater in this work allows us to construct the sensor with cost-effective fabricating resource. These  
12 limitations can be improved by using micro fabrication process. As the sensor working principle relies on the heat  
13 transfer from the heater to the temperature sensing elements, optimizing the surrounding cavities and sensing  
14 element positions may further increase the sensitivity in all directions [45]. Finally, the sensor performance can  
15 be boosted by utilizing sensing element which has high resistance and temperature coefficient of resistance  
16 [14,17,60,61,65], or packing conditions such as pressure or high thermal conductivity gas [19,66–68].**

## 17 VI. CONCLUSION

18 We reported a tri-axis convective accelerometer of millimeter-scale that utilizes a closed-loop heater to  
19 improve the sensing performance. The closed-loop heater concentrated the convectively heated air at the central  
20 part even though there was no heat source underneath, which helped to reduce the cross-effect of the horizontal  
21 acceleration to the vertical acceleration sensing. A numerical simulation was performed and the result was  
22 supported by the experimental work. The tilting test showed small cross-effect. The sensor was also tested by  
23 applying centrifugal acceleration and the linear relation between the output and the acceleration was achieved  
24 up to 20 g. The sensor was fabricated by additive manufacturing and the assembly process was simple, thus  
25 allowing quick and cost-effective prototyping to integrate this device into laboratory-scale projects. In addition,  
26 the device is made of laminated parts and can be potentially compatible with the conventional microfabrication  
27 process for significant reduction in the cost.

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