論文の内容の要旨

Barometric Pressure Sensing Using the Effect of
Fluid Structure Interaction in Cantilever-based Structure
(カンチレバー構造における流体構造連成を利用した気圧計測)

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1. Introduction

MEMS based barometric pressure sensors have been developed for a wide range of applications, including those in automotive systems, medical systems and environmental monitoring. Conventional barometric pressure sensors consist of a differential pressure sensing diaphragm, which is usually capacitive or piezo-resistive or optical type, and a vacuum-sealed cavity underneath. In these researches, pressure sensing normally based on diaphragm deformation, but for small pressure, the deformation is too small to be detectable. To make the diaphragm thinner may solve the above issue to some extent, but the fabrication is rather complicated. In addition, thinner diaphragm becomes fragile and easy to be damaged by high pressure change. Additionally, the fabrication process of vacuum-sealed cavity and the integrated circuits are comparatively complicated and at a high cost. In this paper, I propose a different approach to achieve a highly sensitive barometric pressure sensor, which is based on a piezo-resistive cantilever. In the proposed sensor, an ultra-thin (300-nm-thick) piezo-resistive cantilever was placed on the opening of a cavity, which was used as the reference pressure (**Figure 1**). Here, the piezo-resistive cantilever was used to measure the time-variant differential pressure between the barometric pressure and the cavity's pressure. Because one end of the cantilever is free, the cantilever-based pressure sensors should be 100 times more sensitive than diaphragm-based sensors, considering the same dimensions. With respect to diaphragm types, in our sensor, there is a gap between the cantilever and its surrounding walls such that air can leak through the gap. Noise spectrum analysis has demonstrated that miniaturizing the air-gap enables the sensor to measure pressure changes with a best resolution of 10 mPa order for a gap size of 1.1 μm and cavity volume of 1 ml, providing that the experiment was carried out in low vacuum status.

2. Sensing theory and experiment preparation

The principle for measuring the change in barometric pressure is simple. Let us define the initial state as the state in which the pressure inside the cavity and the ambient pressure are equal. The cantilever does not deform, and there is no air leakage through the air-gap at the initial state. Now, consider the case in which the barometric pressure increases (e.g., due to an altitude change). As a result, the cantilever bends and the gap gradually becomes larger to allow air to leak through the gap. Due to the air leakage, the pressure inside the cavity increases to match the barometric pressure. When the pressure inside the cavity equals the barometric pressure, the cantilever returns to its initial state. The key factor here is the size of the air-gap. Indeed, the behavior of air-leakage through the gap, which is merely a few micrometers wide, is different from the behavior that would be observed in macroscopic space. Here, the shear force (i.e., the viscosity) of the air within the air-gap is dominant and prevents air from leaking through the air-gap. Therefore, the pressure loss due to air leakage becomes small, and the differential pressure experienced by the cantilever increases as the air-gap decreases. In other words, the displacement of the cantilever due to a change in barometric pressure increases for a smaller air-gap. Hence, the sensor's sensitivity can be improved by using a miniaturized air-gap.

In fabrication, the fabricated cantilever was attached to a circuit board by using an instant adhesive (Aron Alpha, Toagosei Company, Ltd.) and UV curable resin (**Figure 1**). The cavity was fabricated from ABS (acrylonitrile butadiene styrene) using a modeling machine, which enabled the cavity volumes to be precisely controlled. Then the circuit board was attached to the opening of the cavity with screws. A plastic O-ring was sandwiched between the circuit board and the cavity to prevent air leak. In all of the test samples, the dimensions of the piezo-resistive cantilever were fixed. The SEM images of the piezo-resistive cantilever are shown in **Figure 2**. The thickness of the piezo-resistive cantilever was 0.3 μm. With this design, the mass of the piezo-resistive cantilever was small enough that the influence of inertial forces on the sensor's response could be neglected. In other words, the proposed sensor is not affected by acceleration. In detail, with the above dimensions, the mass of the cantilever was 7.8×10^{-9} g. For example, let us consider a case in which the cantilever experiences an acceleration of 1 G. The pressure that is applied to the cantilever surface is calculated to be 6.7 mPa, which is negligible.

3. Fluid structure interaction simulation

The simulation physic model is shown in **Figure 3**. Two circular cylinders are considered as the atmosphere and the sensor's cavity. The volume of atmosphere chamber is 6 times larger than that of the cavity chamber. A cantilever beam with an air gap is placed between the two chambers. The dimensions of the cantilever are with thickness of 1 μm. Here, simulation with gap size of 5 μm, 10 μm, 20 μm and 40 μm was carried out. Assume that the differential pressure between the two chambers is kept at 10 Pa by a pressure supplying source. When the pressure supplier is switched off, the differential pressure gradually decreases to 0 Pa due to the air leak through the gap. According to the result in **Figure 4 (a)**, the process of pressure decay is different with different gap size. **Figure 4 (b)** shows the relationship between the natural logarithm of differential pressure with time. This result indicates that the differential pressure decreases in an exponential decay curve of time. Additionally, the logarithmic decrement is proportional to square of gap area (**Figure 5**). Similar simulations for various cavity volumes and various applied pressure were taken. The results demonstrate that the logarithmic decrement is inversely proportional to cavity volume (**Figure 6 (a)**). However, this decrement does not depend on the applied pressure (**Figure 6 (b)**).

4. Evaluation experiments

The first experiment was to confirm the dependence of logarithmic decrement on applied pressure. The change in external pressure makes the cantilever bend and allows air leak through the gap. After the cantilever displacement reaches its peak, it gradually decreases to the initial position. In theoretical calculation, the resistance change of a piezo-resistive cantilever's is proportional to the cantilever's displacement. And the displacement is proportional to the differential pressure. Therefore, the process of differential pressure decay can be derived by recording the resistance change of the piezo-resistive cantilever (**Figure 7 (a)**). The result did well agree with simulation result in which the differential pressure (i.e. cantilever displacement) decreases in an exponential decay curve of time. Additionally, the logarithmic decrement was not dependent on the pressure change (**Figure 7 (b)**). However, in experiments the relationship between decrement factor and gap size in this experiment is a proportional one (**Figure 8 (a)**). This result is different with simulation result. Indeed, due to the ability of simulation processing computer, the gap size in simulation was larger than 5 μm and the cantilever thickness was 1 μm. For a gap size of few microns, the Reynolds number is supposed to be relatively small. Therefore, the different in gap size could bring into a significant difference in air viscosity. This could be the reason for the difference of experiment result and simulation result. Nevertheless, in both of experiment and simulation, the differential pressure decay is confirmed to be an exponential function of time. In addition, the decrement factor is larger for bigger gap size. In experiment, the tendency, in which larger cavity makes longer pressure relaxation process, was also confirmed (**Figure 8 (b)**). According to this fact, the sensor should be designed with small gap size and large cavity in order to improve the sensing performance. In applications, the idea of making larger cavity is not favorable. Hence, the key for this device is to narrowing the gap size as much as possible.

An evaluation on the characteristics of the proposed barometric pressure sensor was carried out over a range from 0.05 Hz to 1 Hz. In this experiment, cantilevers with designed air-gap sizes of 1 μm, 2 μm, 3 μm and 5 μm were fabricated. The actual gap size was 1.1 μm, 2.3 μm, 3.2 μm and 5.9 μm. The cavity volume was precisely controlled at 1 ml, 2 ml and 4 ml. The experimental setup is shown in **Figure 9(a) (b)**. In the rotating experiment, the maximum altitude change of the sensor was 30 cm, which was the diameter of the rotating orbit of the sensor. Therefore, the maximum change in barometric pressure was 3.5 Pa. An accelerometer (HAAM-302B, Hokuriku Electric Industry Co., Ltd, Japan) was used to calculate the position of the sensor, which was obtained by measuring the gravitational acceleration. The sensor's response for rotating frequency of 1 Hz and its sensitivity for various frequencies are shown in **Figure 10(a) (b)**. According to the result, the sensitivity dropped when the rotation rate decreased. This result is reasonable because in the case of the lower rotation rate, air leakage occurred when the barometric pressure changed. Air leakage results in a smaller pressure difference between the upper and lower sides of the piezo-resistive cantilever. Phase lag data for the different air-gap sizes are shown in **Figure 11 (a)**. Here, the phase lag was the phase lag of the sensor compared to that of the conventional accelerometer. The cavity volume was fixed at 4 ml. For a fixed rotation rate, a smaller air-gap size resulted in a smaller phase lag. Because the deformation of the cantilever due to pressure is a simple first-order lag system, we defined the cut-off frequency of the systems to be the frequency at which the phase lag is 45 degrees. The variation of the cut-off frequency for the various gap sizes is shown in **Figure 11 (b)**. This result indicates that by miniaturizing the gap size, the sensor was enabled to measure a smaller range of pressure change rates. The frequency characteristics of the sensor for various cavity volumes and various gap sizes were also investigated. The results are shown in **Figure 12 (a) (b)**. Here, we can observe that a larger cavity enabled the sensor to have a greater response. Moreover, the sensor response for a smaller gap was flatter. In other words, a small gap size was able to maintain high sensitivity even in a low frequency range, which allows us to conclude that by fabricating a small air-gap size and a large cavity volume, better sensitivity can be archived. **Figure 13** shows the result of noise spectrum analysis using a desiccator to pump down the ambient pressure to 0.2 atm. Without influence of light source, mechanical vibration and external air flow, the sensor was proved to be able to measure pressure with a high resolution of 10 mPa with a corresponding bandwidth of 10 Hz. On the whole, considering a bandwidth of sub 100 Hz, the measurement resolution was calculated to be in 10 mPa order.

5. Conclusion

In this study, an approach for measuring barometric pressure with high sensitivity based on a piezo-resistive cantilever was proposed. The simulations and the experiments indicate that the differential pressure changes in an exponential decay curve of time. They both demonstrate that the sensor should be designed with small gap size and large cavity in order to improve the sensing performance. Although the sensitivity and the resolution decreased at lower frequencies, the experimental results show that the sensor can measure pressure changes at a rate of 0.05 Hz with an air-gap size of 1.1 μm and cavity volume of 4 ml. Furthermore, the measurable rate and resolution of pressure change should improve with a smaller air-gap size. Nevertheless, the sensor has a potential of measuring pressure in a range of 10 mPa order for a bandwidth of sub 100 Hz, providing that the experiment was done in low vacuum. This sensor is expected to be used in applications such as automotive navigation or personal mobile devices or acoustic systems.

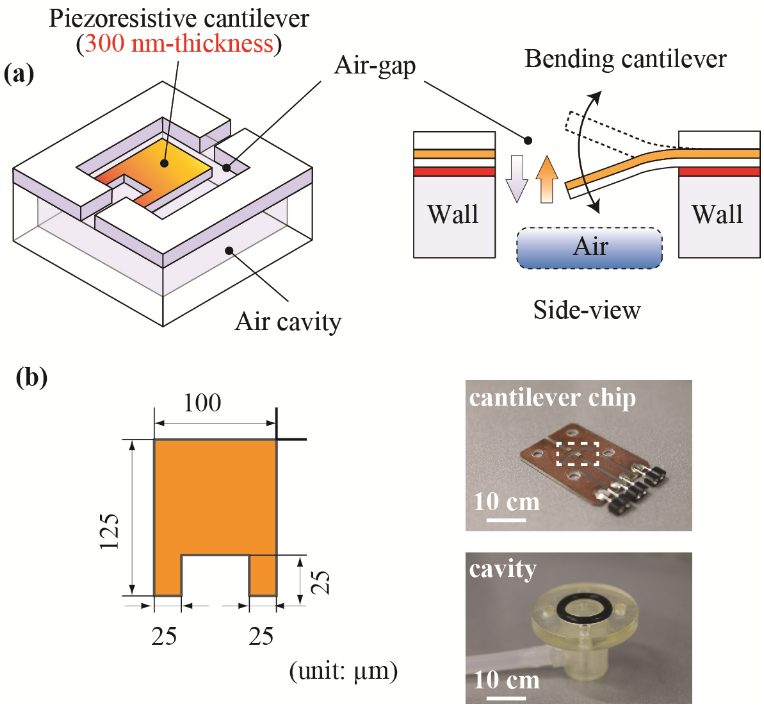

Figure 1: (a) Skeptical diagram of the sensor device. (b) Dimensions of the cantilever and image of the sensor device.

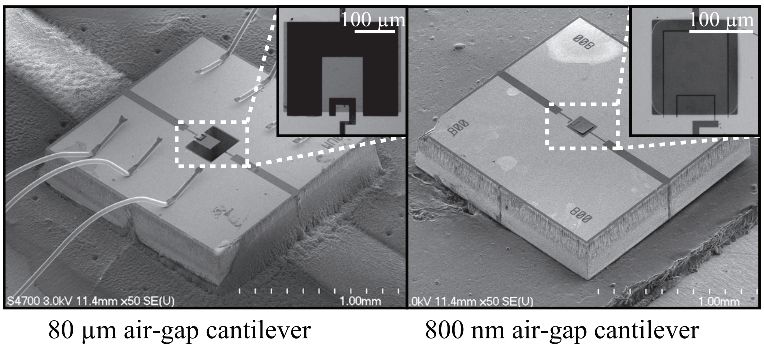

Figure 2: SEM images of the fabricated piezo-resistive cantilever chip

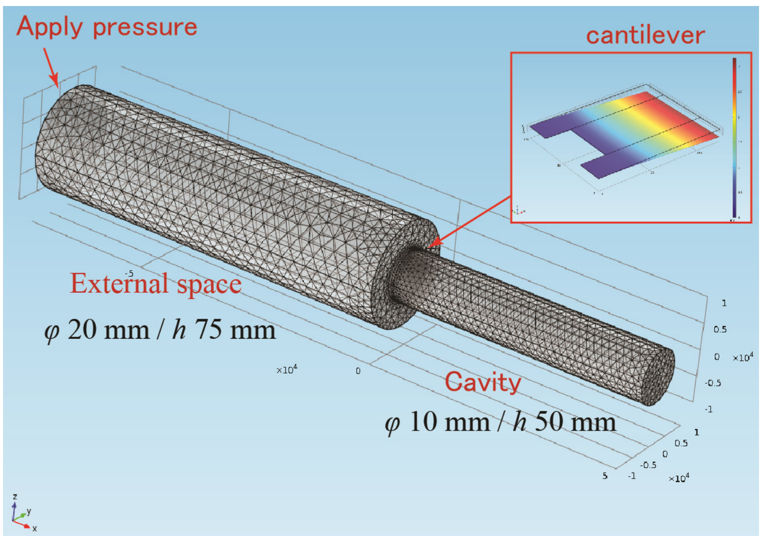

Figure 3: Fluid structure interaction model using a Finite-Element- Method (FEM) simulation (COMSOL Multiphysics).

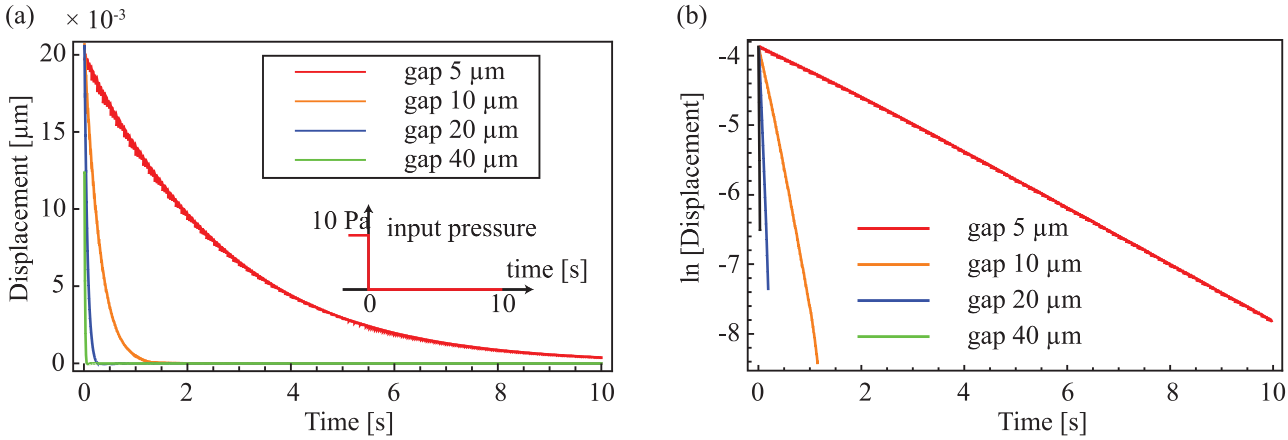

Figure 4: (a) Cantilever displacement with various air-gap sizes. At initial status the differential pressure is kept at 10 Pa and then the input pressure is turned off. (b) Displacement is expressed in terms of logarithm. The result shows that the cantilever's displacement decreases in an exponential function of time.

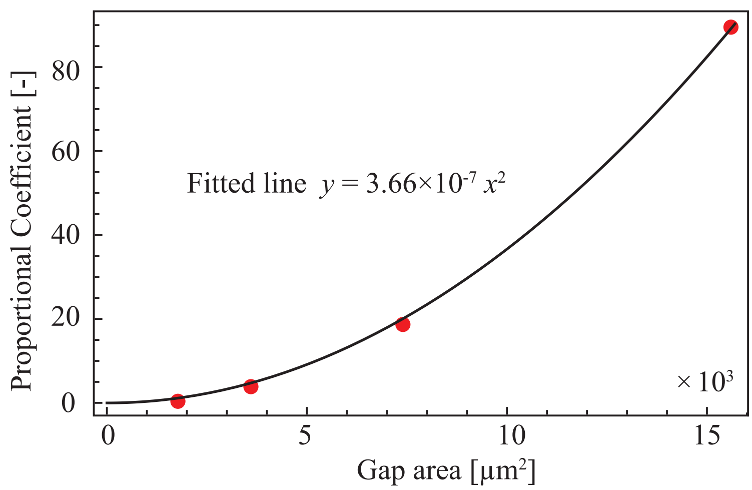

Figure 5: Relationship between logarithmic decrement of displacement and gap area.

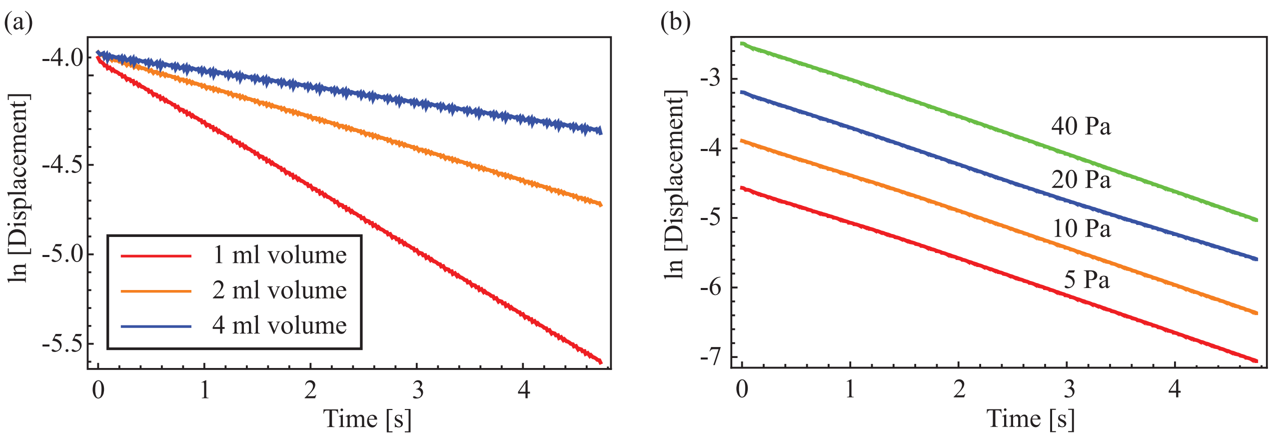

Figure 6: Cantilever displacement decreases in exponential function of time, for various volume and applied pressure.
(a) The result shows that the decrement factor of displacement is inversely proportional to cavity volume.
(b) The result shows that the decrement factor is not dependent on the applied pressure.

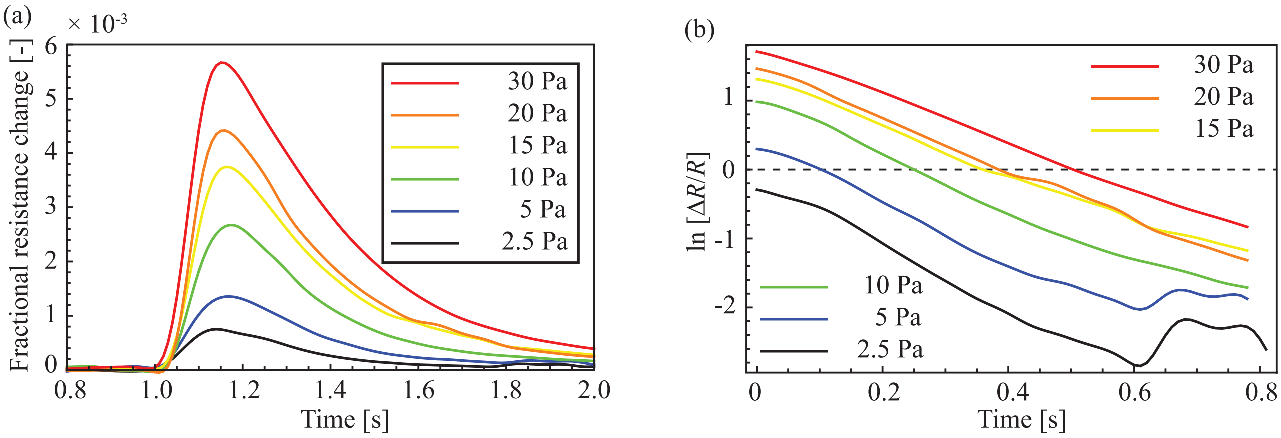

Figure 7: (a) Sensor response for various applied pressures. (b) The result shows that after the peak the cantilever's displacement decreases in an exponential function of time and the decrement factor is not dependent on applied pressure.

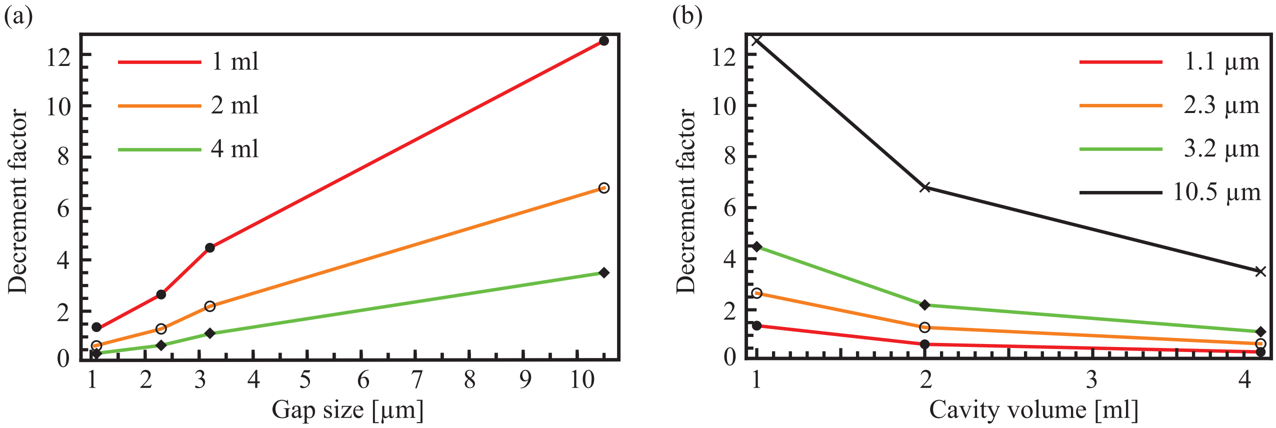

Figure 8: Dependence of decrement factor on (a) gap size (b) cavity volume.

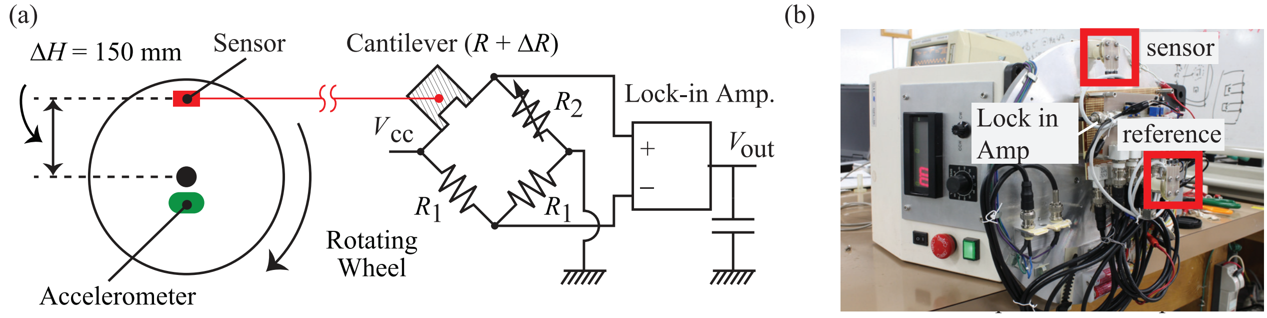

Figure 9: (a) concept and (b) image of the experimental setup with a rotating wheel.

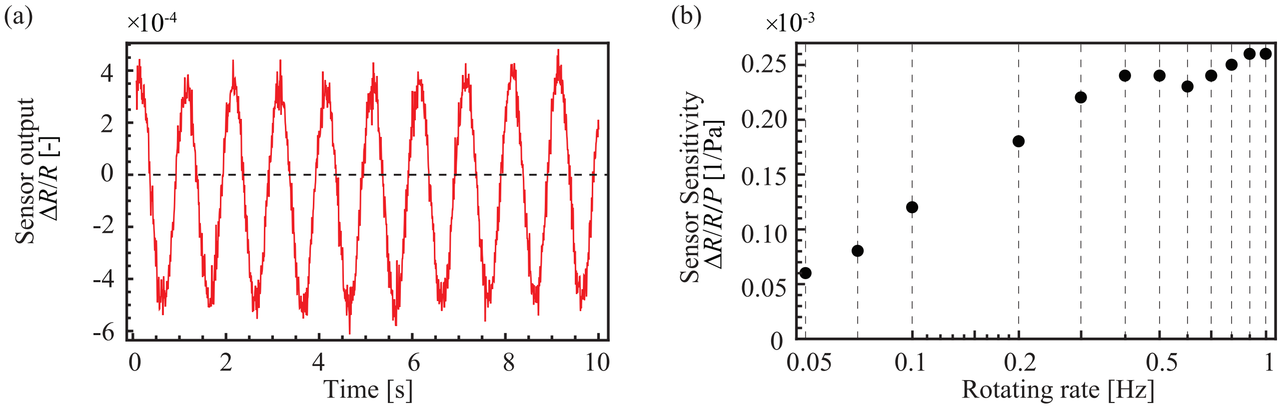

Figure 10: (a) Sensor response for a rotating frequency of 1 Hz (b) Sensor sensitivity (fractional resistance change per 1 Pa) for various the rotating frequencies. The air-gap size was 1 μm, and the cavity volume was 2 ml.

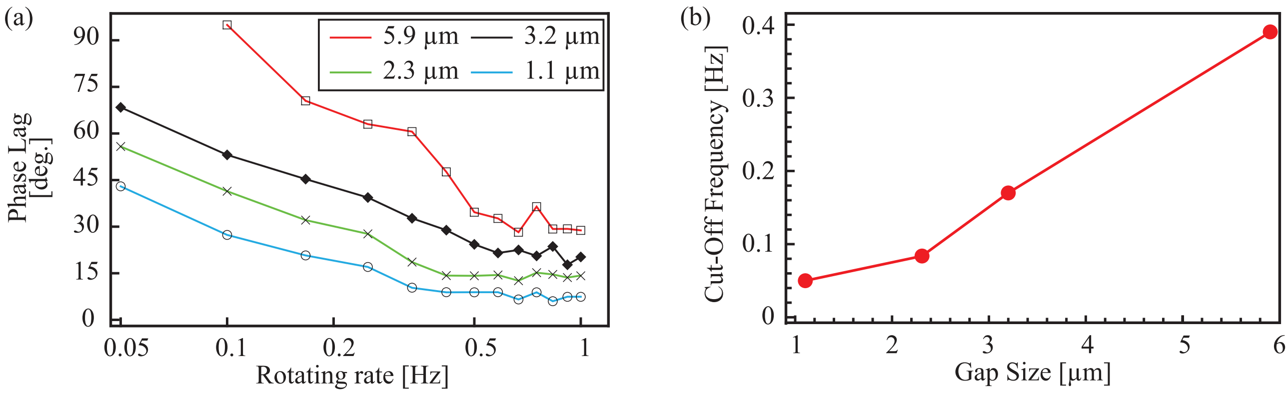

Figure 11 (a) Phase lags for various air-gap sizes with a cavity volume of 4 ml. (d) Cut-off frequencies for different gap sizes with a cavity volume of 4 ml.

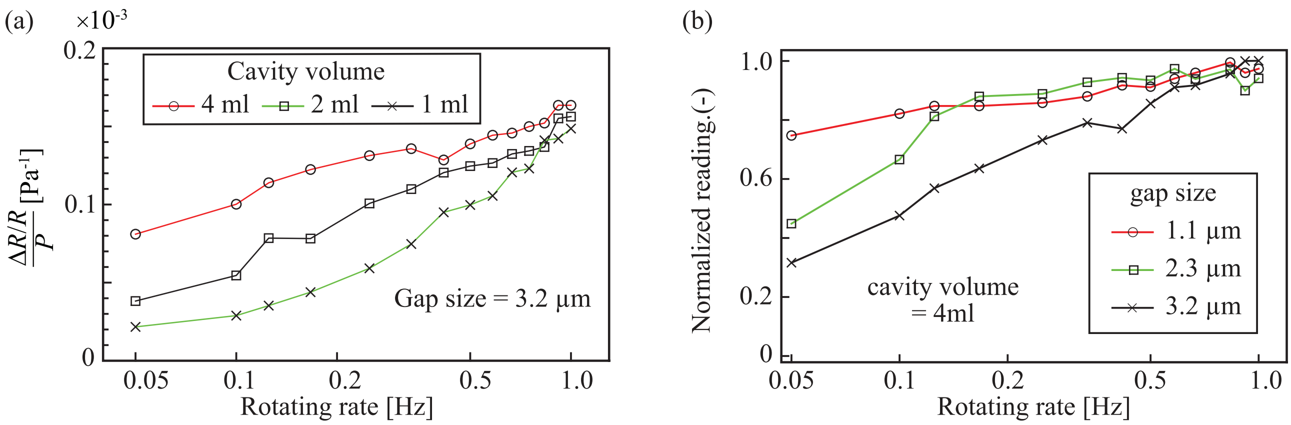

Figure 12: Frequency characteristics of the sensor for various cavity volumes and air-gap sizes. a) The air-gap size was 1 µm, and the cavity volume was controlled to be 1 ml, 2 ml and 4 ml. b)The cavity volume was 4 ml and the air-gap sizes were 1.1 µm, 2.3 µm and 3.2 µm.

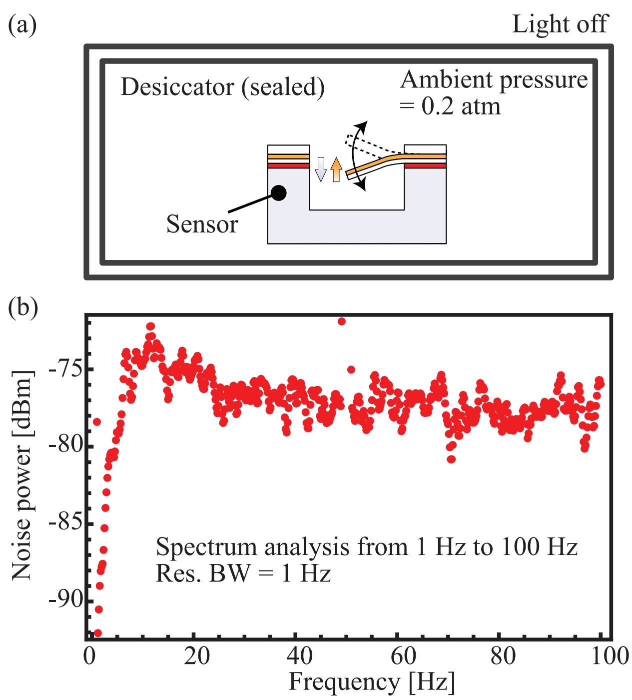

Figure 13: Experiment for evaluating noise and minimum measurement resolution of the sensor. (a) Experimental setup with desiccator in low vacuum. (b) Noise spectrum measured with a network analyzer. The result shows that the measurement resolution of the sensor was 10 mPa for a bandwidth of 10 Hz.