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A MEMS flow sensor applied in a variable-air-volume unit in a building air-conditioning system

M. Shikida[a,*], Y. Yamazaki[b], K. Yoshikawa[b], Kazuo Sato[b]

[a] Center for Micro-Nano Mechatronics, Nagoya University, Chikusa, Nagoya 464-8603, Japan
[b] Department of Micro-Nano Systems Engineering, Nagoya University, Japan

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ABSTRACT

A MEMS flow sensor was applied in a variable-air-volume (VAV) unit, composed of a butterfly damper and a flow sensor, to precisely control the supply of air in a large-scale air-conditioning network system used in a building. The MEMS flow sensor is composed of a hot-wire anemometer with an underside cavity to shorten the response time, and it was fabricated on a 25-μm-thick polyimide film by photolithography and film deposition. The total thickness of the sensor structure is only 525 μm. Four sensors were attached at 90° to each other on the inner surface of an 8-in. duct, and the outputs obtained by the sensors were averaged. The results of an experimental evaluation of the sensor are as follows. First, the averaged sensor output depends on damper angle and the distance of the sensor from the damper. Second, it is higher than that obtained by a similar sensor in a straight duct. Third, a conversion curve was derived and used to calculate flow rate from the obtained outputs of the four sensors fitted in the VAV unit.

1. Introduction

Physical sensors, for example pressure, acceleration, and gyro sensors, have been miniaturized and integrated onto silicon wafers by micro electro-mechanical systems (MEMS) technologies since the 1970s [1–4]. In the automotive and amusement industries, they are now widely utilized. As a MEMS technology, a flow sensor fabricated on a silicon wafer also has a long history, and various types of MEMS flow sensors have been developed. Liu et al. developed a thermal-type flow sensor to detect shear stress [5]. Zhe et al. used a micro-machined cantilever structure for measuring the shear stress [6]. Si-MEMS flow sensors have excellent space and time resolutions, so they are used in mass-flow controllers in semiconductor equipment and fuel-delivery systems used in the automotive industry for precisely controlling gas flow. In 2009, Unnikrishan et al. proposed the MEMS-on-tube assembly to simplify the packaging process used in Si-MEMS [7,8]. They integrated Si-MEMS devices directly in a glass tube, which is compatible with a Swagelok® connector, by using fusion bonding. These and other silicon-based flow sensors are summarized in Refs. [9,10].

The MEMS flow sensor has come into use for medical, aircraft, and water-channel applications, and the novel processes for fabricating flexible MEMS flow sensors have also been developed. For example, Buder et al. detected the flow separation for a specific aerodynamic configuration by the fabricated MEMS flow sensor [11]. Zhu et al. mounted the MEMS sensor on the curved surface of a wing so that it could measure the flow of air over the wing [12]. As for medical applications, Li et al. integrated pressure, temperature, glucose, and oxygen sensors for blood analysis on the flexible film [13]. Naito et al. produced a miniaturized on-wall in-tube flow sensor [14]. They used it to fabricate a catheter-type flow sensor for measuring aspirated- and inspirited-air characteristics [15,16]. Ma et al. applied the MEMS flow sensor for detecting the dynamic wave flow in water channels [17].

Recently, the MEMS flow sensors have been introduced into large-scale air-conditioning network systems to reduce their excessive energy consumption by precisely controlling the air supply to these systems. For example, Shikida et al., installed flexible MEMS flow sensors inside the ducts of such a system and measured the flow rates at the downstream of bent ducts [18]. Normally, a variable-air-volume (VAV) unit, composed of a flow sensor and a butterfly damper, is built into the branch ducts in the system and used to control the air supplied to each room. In the present study, the MEMS flow sensor developed in the previous work was firstly applied to a VAV unit to precisely control the air-flow rate in an air-conditioning system.

2. MEMS flow sensor for VAV control

A schematic view of a large-scale building air-conditioning system is shown in Fig. 1. The air-conditioned air is produced in the air-conditioning system located outside the building and delivered

* Corresponding author.
E-mail address: shikida@mech.nagoya-u.ac.jp (M. Shikida).

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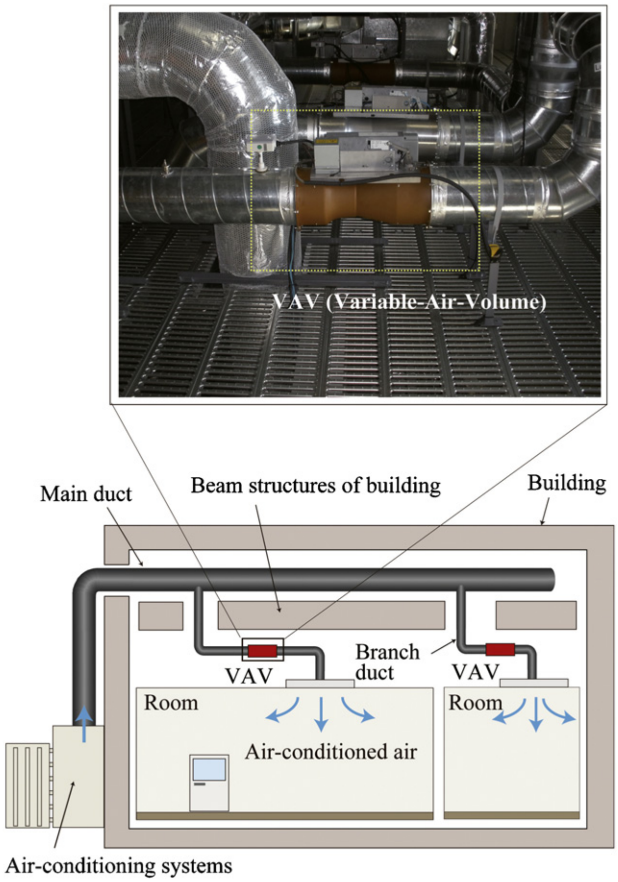

Fig. 1. Variable-air-volume unit and large-scale building air-conditioning system.

to each room by a duct network. The configuration of the branch duct for supplying the air to each room is complicated (because the beam structures of the building are formed first during construction of the building, and the duct network is then installed in the limited empty space in the ceiling of the building). Normally, the VAV unit is fitted to the branch ducts that control the flow rate of air to each room. However, a conventional VAV system has the following two problems.

(1) A propeller-type flow sensor, which is used to detect the flow rate in the duct, causes a high flow resistance. As a result, the flow sensor itself produces a large pressure loss.
(2) First, air-conditioned air is delivered from the main duct to the branch ducts. Controlled by the VAV in each branch, the air is then supplied to each room. As a result, the air flow in one branch duct is affected by that in the other branch ducts. The VAV in each branch duct is thus actively operated so that the air flow for each room is precisely controlled. Under such an unsteady flow condition, the MEMS flow sensor should be placed downstream of the damper, because it can measure the flow rate for each room directly. However, the air flow downstream of the damper is complicated, because of the inhomogeneous distribution of flow rate. It is thus difficult to accurately measure flow rate by a single-point flow measurement, like that provided by a propeller-type flow sensor.

To overcome these problems, a thin flexible MEMS flow sensor was firstly applied in the VAV unit (Fig. 2). The sensor is composed of a hot-wire anemometer (heater) and a cavity under it to shorten the response time. It was fabricated on a 25-μm-thick polyimide film by photolithography and film deposition. The total thickness of

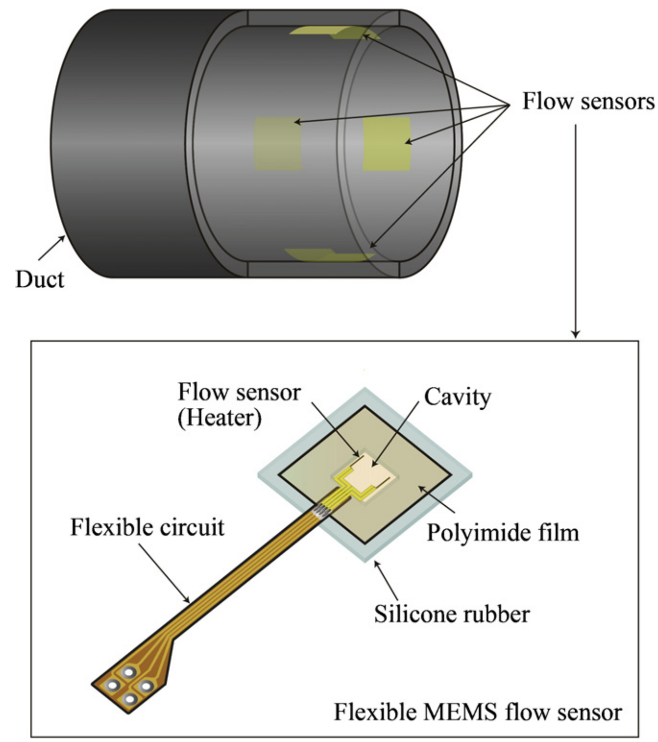

Fig. 2. Flexible MEMS flow sensor and its position on inside surface of duct.

the sensor structure is 525 μm, which is low enough to drastically reduce the air-flow resistance of the sensor structure.

In a previous work, a ring-shaped sensing element for measuring flow rate under asymmetric flow in the radial direction was proposed [19]. The output of the sensing element was insensitive to the radially asymmetric characteristics of the flow velocity distribution, because it averaged a circumferentially non-uniform velocity distribution under a distorted flow condition. As a result, the sensor output a constant value against the corresponding flow rate even if the velocity distribution did not attain an axisymmetric condition. To overcome the second above-mentioned problem, four sensors were therefore attached to the inside surface of the branch duct, and the flow rates measured at four points were averaged (Fig. 2).

Three different types of detection mechanisms, namely, thermal anemometry, calorimetric flow sensing, and time-of-flight sensing, are normally used in a MEMS flow sensor [9,10]. Thermal anemometry is used in this study, because it has a relatively large measurement range and is the simplest. It detects a flow by measuring the heat dissipated from the heater to the fluid by forced convection. The relationship between dissipated power Q and flow velocity U is given by King's law [20]:

$$Q = (A + BU^n) \cdot (T_h - T_0) \quad (1)$$

where A, B, and n are constants that depend on the geometry of the heater element; T_h and T_0 are the temperatures of the heater and the body of fluid, respectively. If the heater were infinitely long, n would be 0.5. However, n differs from 0.5 in the case of a heater with finite length [9]. A constant temperature (CT) is frequently used in flow-rate measurements. In CT mode, the temperature of the heater is kept constant by a feedback circuit to shorten the response time of the sensor, and the flow rate is calculated from the feedback voltage. The electrical energy supplied to the heater