Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Ultrasonic Airflow Meter in Greenhouse Using Acoustic Reflection against Wall

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In this paper, we described an ultrasonic airflow meter in a greenhouse using an acoustic reflection against a wall. The ultrasonic airflow meter is available for measuring the spatial mean wind velocity and direction, which consists of two sound probes and the wall of the greenhouse. Use of sound probes has advantage that the airflow accumulated along sound paths from a loudspeaker to a microphone is obtained in contrast to point measurements. The wind velocity and direction are calculated from times of flights (TOFs) of direct and reflected signals. The wind velocity and direction were measured in a greenhouse of 7.4 m × 29.0 m under artificial winds generated from two electric fans located at the one side of the greenhouse. In addition, we detected air convection generated from two pairs of fans. These were measured every 20 seconds for 120 minutes. Regarding the measured; by the proposed airflow meter and a reference; by a conventional one, their root-mean-square values were 0.16 and 0.19 (m/s). This airflow meter using the acoustic reflection against the wall is convenient to measure the wind velocity and direction in large-size facilities such as the greenhouse.

1 Introduction

It is necessary to establish efficient air-conditioning systems for comfortable working conditions such as offices and improving the rate of production of farmgoods. Therefore, it is desired to keep an appropriate temperature in whole spaces. In addition, since the efficient air-conditioning systems are also important from the standpoint of saving of energy [1], it is also important for keeping the appropriate temperature for measurement and control of winds arisen by ventilation systems. In recent years, facilities such as offices and greenhouses used in agriculture tend to become large. However, conventional anemometers to measure wind velocities and directions can only measure vicinity of the instrument. Typical measurement methods by the conventional ones for measuring large spaces have two methods. One is the measurement method using a single anemometer and the other is that using plural anemometers. These measurement methods have problems such as the measurement accuracy, the increase of instruments and the occupation of spaces [2]. Therefore, the anemometers that can effectively measure wind velocity and direction in large spaces at one time are desired [3]. A measurement system using sound probes is one of such a type of devices [4-6].

The sound probe consists of a loudspeaker (SP), a microphone (MIC), and a propagation path. It is very favorable for measuring temperature, wind velocity, and direction of the propagation paths by exploiting noncontact and area measurement ability. Because sound velocities depend on temperature, wind velocities, directions, and other parameters of the propagation paths, the mean values of such parameters can be determined from the times of flights (TOFs) on the propagation paths between the SP and the MIC. It is only necessary to locate the sound probes parallel to the wind direction if the wind direction stays constant all the time. However, it is not always true that the wind direction remains unchanged. Thus, it is necessary to measure the two-axis wind velocity and direction. The conventional anemometer consists of four pairs of the sound probes for the two-axis measurements. Therefore, the number of devices for each instrument increases and the constructions of systems become complicated. However, the two-axis wind velocities can be measured by only two pairs of sound probes by use of an acoustic reflection [5-7]. By using, the number of devices can decrease and the construction of systems can facilitate.

In this paper, we propose an ultrasonic airflow meter using an acoustic reflection against a wall. We measured wind velocities and directions using the proposed airflow meter and calculated volume velocity. The airflow meter utilizes the acoustic reflection against the wall to measure the wind velocity and direction in the region along the wall not in free spaces but in tunnels or large constructions. Accordingly, it is very efficient to measure the two-axis mean wind velocities and directions by use of the acoustic reflection against the wall.

2 Principle of measurements

2.1 Two-axis measurements

Figure 1 shows a schematic diagram of an ultrasonic airflow meter using an acoustic reflection against a wall. This consists of two pairs of SPs, MICs, and a single wall. The proposed airflow meter forms a triangle of arbitrary shape with three devices. The sound probe of the reflected path is constructed using the acoustic reflection against the wall.

The wind velocity can be measured from apparent sound velocity and sound velocity can be measured without the effect of wind using the two sound probes. One consists of SP_1-wall-MIC_1 and the other consists of SP_2-wall-MIC_2. This airflow meter can be used to measure the two-axis mean wind velocity in the plane formed by the SP, MIC, and a reflected point. Wind velocity vector, $\boldsymbol{w}$ is decomposed of its *x*- and *y*-components, w_x and w_y in the coordinates along the direct path and θ is defined as the wind direction. The origin of the *x*-*y* coordinate is the location of SP_1. The sound velocity, c, distance of the direct path, L_1, and two TOFs of each direct path, t_{d1} and t_{d2}, are expressed as

$$t_{\mathrm{d1}} = \frac{L_1}{c\cos\phi_1 + w_x}, \tag{1}$$

$$t_{\mathrm{d2}} = \frac{L_1}{c\cos\phi_1 - w_x}, \tag{2}$$

where ϕ_1 denotes the angle by which the sound wave is deviated by the wind. The mean sound velocity, c is obtained using the sum of the inverses of eqs. (1) and (2) as

$$c = \frac{L_1}{2}\left(\frac{1}{t_{\mathrm{d1}}} + \frac{1}{t_{\mathrm{d2}}}\right). \tag{3}$$

The *x*-component of $\boldsymbol{w}$, w_x, is straightforwardly obtained using the difference of the inverses of eqs. (1) and (2) as

$$w_x = L_1\left(\frac{1}{t_{\mathrm{d2}}} - \frac{1}{t_{\mathrm{d1}}}\right). \tag{4}$$

The wind velocity vector, $\boldsymbol{w}$ is decomposed to its x'- and y'-components, w'_x and w'_y in the x'-y' coordinates along the path, SP_1-wall, and $\boldsymbol{w}$ is also decomposed to its x''- and y''-components, w''_x and w''_y in the x''-y'' coordinates along the path, wall-MIC_1. The origins of the x'- and y'-, and x''- and y''-coordinates are at the location of the SP_1 and wall, respectively. The TOF of SP_1-wall-MIC_1, t_{r1}, and that of SP_2-wall-MIC_2, t_{r2}, are expressed as

$$\begin{aligned} t_{\mathrm{r1}} &= t_{\mathrm{r11}} + t_{\mathrm{r12}} \\ &= \frac{L_2}{c\cos\phi_2 + w'_x} + \frac{L_3}{c\cos\phi_3 - w''_x}, \end{aligned} \tag{5}$$

$$\begin{aligned} t_{\mathrm{r2}} &= t_{\mathrm{r21}} + t_{\mathrm{r22}} \\ &= \frac{L_3}{c\cos\phi_3 + w''_x} + \frac{L_2}{c\cos\phi_2 - w'_x}, \end{aligned} \tag{6}$$

where L_2 and L_3 denote the distances of each reflected paths, SP_1-wall and MIC_1-wall. ϕ_2 and ϕ_3 denote the angles by which the sound waves are deviated by the wind. In eqs. (5) and (6), w'_x, w'_y, w''_x, and w''_y are expressed as

$$\begin{cases} w'_x = w_x \cos\alpha + w_y \sin\alpha \\ w'_y = w_y \cos\alpha - w_x \sin\alpha \end{cases}, \tag{7}$$

$$\begin{cases} w''_x = w_x \cos\gamma - w_y \sin\gamma \\ w''_y = w_y \cos\gamma + w_x \sin\gamma \end{cases}, \tag{8}$$

and eqs. (5) and (6) are expanded as

$$\begin{aligned} &(t_{\mathrm{r}} \sin\alpha \sin\gamma) w_y^2 \\ &+ \begin{Bmatrix} t_{\mathrm{r}} c(\sin\alpha + \sin\gamma) \\ + t_{\mathrm{r}} w_x (\cos\alpha \sin\gamma - \sin\alpha\cos\gamma) \\ -(L_2 \sin\gamma + L_3 \sin\alpha) \end{Bmatrix} w_y \\ &+ \begin{Bmatrix} t_{\mathrm{r}} c^2 - t_{\mathrm{r}} w_x^2 \cos\alpha\cos\gamma \\ + t_{\mathrm{r}} c w_x (\cos\alpha - \cos\gamma) \\ + L_2(w_x\cos\gamma - c) - L_3(w_x \cos\alpha + c) \end{Bmatrix} = 0, \end{aligned} \tag{9}$$

$$\begin{aligned} &(t_{\mathrm{r}} \sin\alpha \sin\gamma) w_y^2 \\ &+ \begin{Bmatrix} t_{\mathrm{r}} c(\sin\alpha + \sin\gamma) \\ + t_{\mathrm{r}} w_x (\cos\alpha \sin\gamma - \sin\alpha\cos\gamma) \\ +(L_2 \sin\gamma + L_3 \sin\alpha) \end{Bmatrix} w_y \\ &+ \begin{Bmatrix} t_{\mathrm{r}} c^2 - t_{\mathrm{r}} w_x^2 \cos\alpha\cos\gamma \\ + t_{\mathrm{r}} c w_x (\cos\alpha - \cos\gamma) \\ - L_2(w_x\cos\gamma - c) + L_3(w_x \cos\alpha + c) \end{Bmatrix} = 0, \end{aligned} \tag{10}$$

where α, β, and γ denote each interior angle of the proposed airflow meter. w_y is obtained by solving eqs. (9) and (10) using eqs. (3), (4), (7), and (8). Then, by using the obtained w_x and w_y, the spatial mean wind velocity, w and wind direction, θ can be calculated.

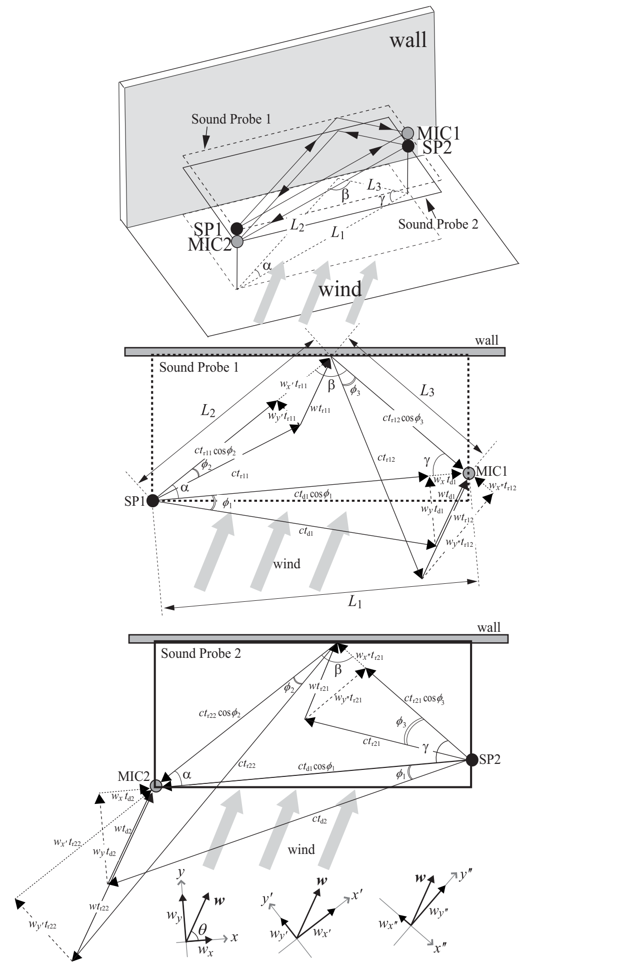

Fig.1 Schematic diagram of an ultrasonic airflow meter using an acoustic reflection against a wall. Wind velocities and directions are determined from the times of flights.

2.2 Measurements of the wind velocity component parallel to the wall

Figure 2 shows a schematic diagram of a measurement of wind velocity component parallel to the wall. The wind velocity vector of the parallel component to the wall is defined as $\boldsymbol{w}_X$. And, the origin of the X-Y coordinate is SP_1. When it assumes that the vertical wind velocity component has little influence on the TOFs, eq. (5) is expressed as

$$t_{\mathrm{r1}} = \frac{L_2}{c + w'_x} + \frac{L_3}{c + w''_x} \tag{11}$$

In addition, the TOF from SP_1 to wall is expressed as

$$t_{\mathrm{r11}} = \frac{L_2}{L_2 + L_3} t_{\mathrm{r1}} = \frac{L_2}{c + w'_x} \tag{12}$$

and w'_x is obtained from eq. (12) as

$$w'_x = \frac{L_2 + L_3}{t_{\mathrm{r1}}} - c \tag{13}$$

w_X is straightforwardly obtained using eq. (13) as

$$w_X = w'_x \cos q \tag{14}$$

where θ denotes the angle between the X coordinate and the propagation path of SP_1-wall.

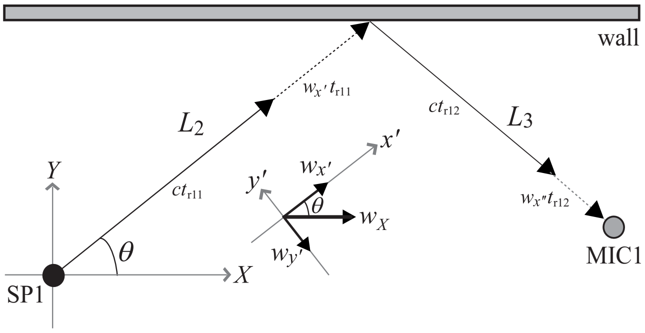

Fig.2 Schematic diagram of the measurements of wind velocity component parallel to the wall.

3 Experimental verification

Figure 3 shows a schematic diagram of the experimental setup. Wind velocities and directions were measured in a greenhouse of 7.4 m × 29.0 m. The wall of the greenhouse is made of glass. These were measured under two wind conditions. In Fig. 3, Experiment (a) shows the experimental setup under winds generated from two large electric fans located at the one side of a measurement space and Experiment (b) shows that under winds generated from two pairs of fans located at each side of the measurement space. The proposed airflow meter used in these experiments has a triangle of arbitrary shape. The shape is determined from the length, L_1, L_2, and L_3 (m) of each propagation path. This airflow meter has (L_1, L_2, L_3) = (22.1, 14.4, 10.3). The SP and the MIC are SD-9D4B (Clarion) and CMS-64 (Bousung Electron), respectively. The transmitted and received signals were processed using a personal computer (Pentium III 750 MHz, 256 MB-RAM). The DAQ Card-6062E (National Instruments) was used as both the analog-to-digital (A-D converter) and digital-to-analog (D-A converter) converter. The sampling frequency of the A-D and D-A converter was 250 kHz. The transmitted signals were chirp signals of 5.0 ± 2.5 kHz of ten waves. The TOFs were determined from the cross correlation of the transmitted and received signals. The measured TOFs were averaged by five measurements, and then the wind velocities and directions were calculated from the measured TOFs. The wind velocities and directions were measured every 20 seconds for 120 minutes in each experiment. Reference values of wind velocities and directions were measured using four conventional ultrasonic anemometers (81000, Young). These conventional anemometers were located at the central part of the measurement space.

4 Measurement results

4.1 Experiment (a)

Figure 4 shows a schematic diagram of experimental processes and measurement results of the measured w_x and w_y values and the mean value of the references in Experiment (a). The four anemometers are defined as Ref. 1, Ref. 2, Ref. 3, and Ref. 4. I, II, and III indicate the time division from 0 to 120 (min). Each conventional anemometer measured wind velocities and directions as the

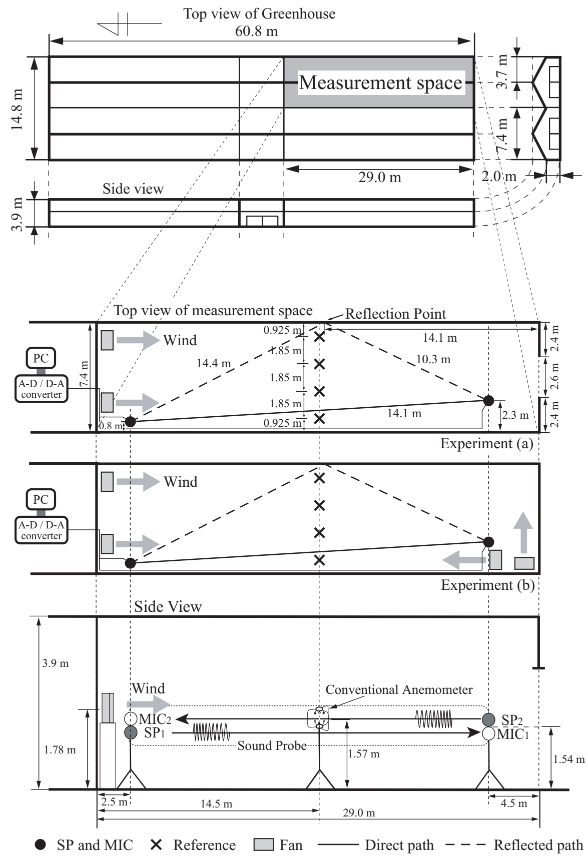

Fig.3 Experimental setups. The experiments were carried out under the different air flows in the greenhouse.

representative value of each area in the measurement space. Wind velocities and directions were measured opening a door of each side of the greenhouse on I. Then, those are measured under winds generated from two large electric fans located at the one side of the measurement space on II and measured stopping the two fans on III. The root-mean-square (RMS) values of the wind velocity of the measured and the reference from 0 to 120 (min) are 0.16 and 0.19 (m/s), respectively. In addition, the RMS values of w_x of the measured and the references on II were 0.18 and 0.21 (m/s), respectively. Furthermore, those of w_y on II were 0.11 and 0.01 (m/s), respectively. The measured w_x value was lower than the references. It is considered that wind velocities were low at the southern part of the measurement space. And, the cause of the error in w_y between the measured and the references is considered as the local turbulence in the measurement space.

4.2 Experiment (b)

Figure 5 shows a schematic diagram of experimental processes and a measurement result of the measured w_X values and the mean w_X value of the references in Experiment (b). IV, V, and VI show the each time division from 0 to 120 (min). Wind velocities were measured without the wind flow from two pairs of fans on IV. Then, those are measured under winds generated from the two pairs of fans located at the each side of the measurement space on V and measured after stopping the all fans on VI. The wind velocity of the parallel component to the wall is defined as w_X. The RMS values of w_X of the measured and

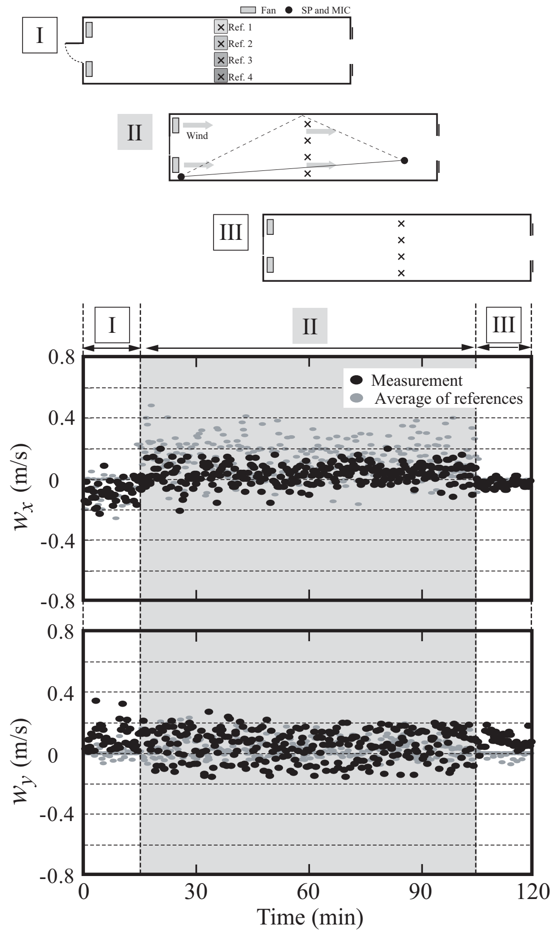

Fig.4 Schematic diagram of experimental processes and measurement results of the measured w_x and w_y values and the mean value of the references in Experiment (a).

the reference from 0 to 120 (min) are 0.024 and 0.018 (m/s), respectively. In addition, that of the measured and the references on V were 0.03 and 0.023 (m/s), respectively. The volume velocity of the calculated w_X is in agreement with that of the references.

4.3 Volume velocity

Figure 6 shows a schematic diagram of a cross section at the position of the four conventional anemometers of the measurement space. Each value of the wind velocity and direction was defined as representative values of each area in the measurement space. The volume velocity of air was calculated in these areas, 7.4 m × 0.01 m. Volume velocity, Q is calculated as

$$Q\left(\mathrm{m}^3/\mathrm{min}\right) = w\left(\mathrm{m}/\mathrm{min}\right) \times A\left(\mathrm{m}^2\right) \qquad (15)$$

where w and A denote the mean wind velocity rate per unit of time and the cross section. Table 1 shows calculation results of the air volume of the measured and the references. In experiment (a), the measured mean wind velocity and the references on II were 0.16 and 0.162 (m/s), respectively. The volume velocity calculated by the proposed airflow meter generally agreed with those of the references. In experiment (b), the measured mean wind velocity and the references on V were 0.02 and 0.01 (m/s), respectively. The volume velocity was different between the measured and the references. It was considered that the mean wind velocity of the references shows that global air flow was

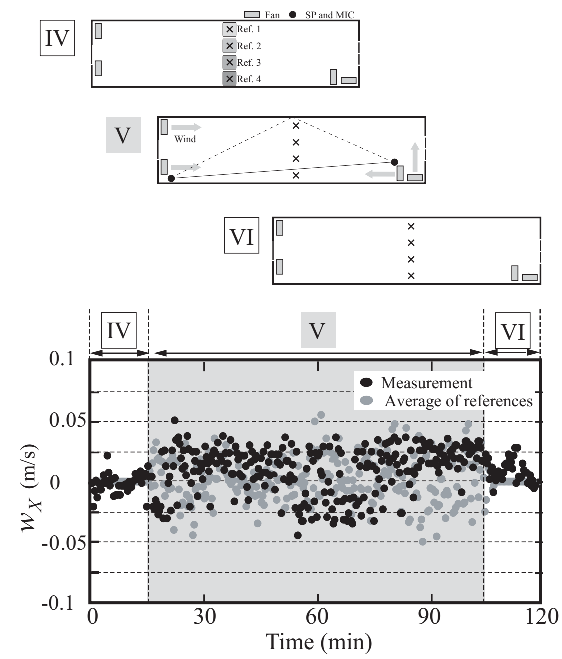

Fig.5 Schematic diagram of experimental processes and a measurement result of the measured w_X values and the mean w_X value of the references in Experiment (b)

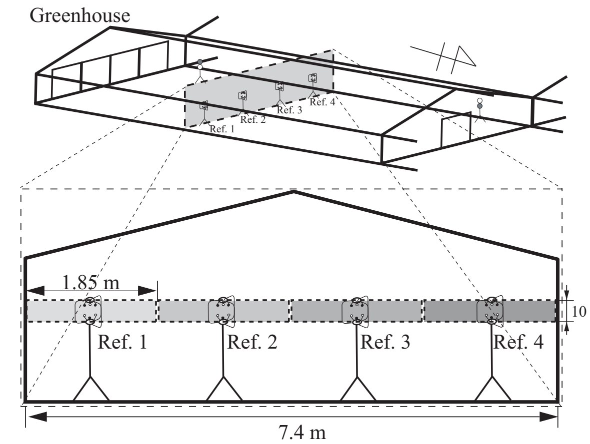

Fig. 6 Schematic diagram of a cross section at the position of the four anemometers of the measurement space.

Air volume of the measured and the references on II and V

	Experiment (a)		Experiment (b)	
	w (m/s)	Volume velocity (m³/min)	w_X (m/s)	Volume velocity (m³/min)
Ref. 1	0.008	0.08	0.13	5.77
Ref. 2	0.25	2.8	-0.16	-7.1
Ref. 3	0.2	2.2	-0.09	-4.0
Ref. 4	0.19	2.16	0.17	7.55
Reference	0.162	7.19	0.01	0.56
Measured	0.16	7.1	0.02	1.12

Table 1 w, w_X and volume velocity of the measured and the references on II and V in Experiment (a) and (b)

very small in this case. Therefore, the proposed airflow meter can be efficiently used to measure the mean volume velocity of the wind flow such as the laminar flow.

5 Conclusion

The wind velocities and directions were measured with an ultrasonic airflow meter using an acoustic reflection against a wall in a greenhouse. This airflow meter uses two sound probes, which consist of two pairs of SPs and MICs and a single wall. The SPs, MICs, and a wall form a triangle of arbitrary shape with three devices. Two experiments were performed under two wind. One is Experiment (a) that the wind velocities and directions were measured under winds generated from two large electric fans located at the one side of the measurement space. The other is Experiment (b) that those were measured under winds generated from two pairs of fans located at each side of that. In Experiment (a), the root-mean-square (RMS) values of w_x of the measured and the references on II were 0.18 and 0.21 (m/s), respectively. And, those of w_y on II were 0.11 and 0.01 (m/s), respectively. In Experiment (b), the RMS values of w_X of the measured and the references on V were 0.03 and 0.023 (m/s), respectively. In addition, the volume velocity was calculated at the part where the four conventional anemometers were put. The volume velocity calculated by the proposed airflow meter globally agreed with those of the references in Experiment (a). In experiment (b), the volume velocity was different between the measured and the references. However, the measurement results depend on the position of a conventional anemometer when only one conventional anemometer measures the wind flow in a large space. In addition, the volume velocity depends on ventilation systems, cultivation conditions of agricultural crops and forms of facilities in large greenhouses. It can be considered that the volume velocity measured using the proposed airflow meter agrees with the references considering the difference of the measured area. From these results, it is verified that the wind velocity, direction and volume velocity can be measured with the proposed airflow meter using the acoustic reflection against the wall. In addition, this airflow meter is convenient to measure the wind velocity and direction in large-size facilities such as the greenhouse.

Acknowledgments

This work was supported in part by a Grant-in-Aid for Scientific Research (B) (No. 17380149) from the Japan Society for the Promotion of Science. The authors thank the National Institute for Rural Engineering for the use of the greenhouse.

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