Micrometeorological Measurements in Field
Using Long Base Line Sound Probes

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Abstract

A measurement method of air temperature, wind vector for micrometeorological measurements using long base line sound probes is described. The sound probe can nondestructively measure mean values of micrometeorological parameters along the base line. Bi-directional sound probe was used for detecting wind vector. Four acoustic sensors were installed at four square tops. Two sound probes which connect the diagonal acoustic sensors are perpendicular to each other at the center, and the lengths are 20 m. Experiment was performed in about 200 m² open field. The results of the air temperature and wind vector agree well in long periodic changes with references.

1. Introduction

The Japanese "Law of Meteorological Services" was amended in 2003[1], and then many private enterprises have been able to join in the meteorological business. In addition, a diversity of life styles and production activities has led to the close connection between meteorology and our social or economical activities. Therefore, the meteorological observation has been performed in many fields; transportation, agriculture[2-4], industry and so on. By the scales of the target atmospheric motion, meteorology is generally classified into three categories; micro-, meso- and macro-meteorology[5]. Micrometeorology deals with the exchange of heat, mass and momentum occurring continuously between the atmosphere and the earth’s surface[5]. Micrometeorology is characterized by the parameters such as air temperature and wind vector. However, the conventional air temperature and wind vector measurements in meteorology have been a "one point measurement", using the solid-sensor like alcohol thermometers or thermocouples although the target of the measurement was large space. Therefore, a temperature distribution in the space has caused measurement error sometimes. The time average had to be conducted in acquired data in order to eliminate the local characteristic.

In this paper, we aim at the realization of micrometeorological measurements in fields using long base line sound probes. In this system, new performance of "region measurement" has been added by the use of an acoustical technique. The sound probe measures nondestructively the mean values of atmospheric parameters in real time, using the sound's characteristic that acquires spatial information along the propagation path. We have studied the micrometeorological measurement in micro-scale space using one sound probe[6-8]. However, one sound probe cannot measure the wind vector.

2. Principle of Measurement

2.1. Measurement of time of flight (TOF)

Schematic diagram of bi-directional sound probe is shown in Fig. 1. The sound probe is a unique instrument for measuring a time of flight (TOF) of sound that propagates from a speaker (SP) to a microphone (MIC) in order to measure air temperature and the component of the wind velocity vector simultaneously. The sound probe consists of a pair of SP and MIC, propagation path and a personal computer (PC) used as a signal processor. The SP and MIC on both sides of the measurement space are facing each other. The base line

Fig. 1 Schematic diagram of bi-directional sound probe to measure the air temperature and the component of the wind velocity vector simultaneously.
of the sound probe is an area along the propagation path. The probing sound is generated as a burst sound by the PC and is launched from the SP. Then the probing sound propagates to the MIC nearly along the base line. The propagation velocity of the sound is varied by the spatial conditions of an air temperature and a wind. Since the probing sound propagates along the base line, the TOF of the sound acquires information of the measurement space.

The TOF is calculated by the cross correlation between transmission signal and received signal. Using the TOFs, we can measure spatial mean values of micrometeorological parameters; the air temperature, the wind velocity vector. In this paper, the probe has bi-directional propagation paths in order to measure the air temperature and the components of the wind velocity vector simultaneously. A chirp sound is adopted as the probing sound. The chirp sound is a frequency-modulated signal which is expressed as follows:

$$s(t) = \begin{cases} \text{Asin} \left[ 2\pi \left( f_0 + \frac{\Delta f}{T} t \right) \right], & 0 \leq t \leq T, \\ 0 & \text{otherwise} \end{cases}$$

(1)

where $f_0$ denotes a center frequency, $\Delta f$ a frequency shift, $T$ a time of the burst wave and $A$ an amplitude. We adopted the down chirp signal that the frequency decreases continuously in linear rate within $T$. The advantage of the chirp signal is accurate detection of the TOF in a cross-correlation process.

Figure 2 shows a typical flight path of the probing sound which propagates in the space with the spatially different wind fields. The propagation path has been divided into a unit cell of $N$ piece. Micrometeorological condition within each unit cell is uniform. The TOF of the sound is the sum time of the sound propagation through each unit cell. Therefore, the bi-directional TOFs from SP1 to MIC2, $t_{12}$, and from SP2 to MIC1, $t_{21}$, are calculated as follows:

$$t_{21} = \sum_{n=1}^{N} \frac{L}{N} \frac{c_n \cos \theta + v_{pn}}{c_n},$$

(2)

$$t_{12} = \sum_{n=1}^{N} \frac{L}{N} \frac{c_n \cos \theta - v_{pn}}{c_n},$$

(3)

$$\theta = \sin ^{-1} \left( \frac{v_{pn}}{c_n} \right),$$

(4)

where $v_{pn}$ denotes the wind vector component parallel to the base line in the $n$-th unit cell, $c_n$ the sound velocity in the $n$-th unit cell, $\bar{v}_n$, the spatial mean value of the wind velocity vector component $v_{pn}$ normal to the base line, $\bar{c}$

the spatial mean value of the sound velocity $c_v$. Generally, it is difficult to identify an arrival time of the sound of the long distance. In order to improve the signal to noise ratio (SNR), the same burst waves are launched several times. The TOF is measured from an average of the received signals. In addition to the above-mentioned, the SNR of the received signal is extremely small by the effects of the pulse compression and correlation operation.

2.2. Calculation for micrometeorological parameters

The air temperature is measured from the sound velocity using a relationship expressed as follows:

$$T = \frac{T_0}{331.32} c^2 - T_0,$$

(5)

where $T_0$ denotes the air temperature, $c$ the sound velocity and $T_0 = 273.15$ K. The TOF easily receives the influence of the wind. The wind velocity vector consists of two parallel and normal components to the base line. The influence of the parallel component is canceled in an average of bi-directional propagation velocity. In the ordinary environment, the average value nearly equals to the parallel component of the sound velocity vector, and then the following approximate expression is adequate:

$$\bar{v}_{\cos \theta} = \frac{1}{2} \left( \frac{L}{t_{21}} + \frac{L}{t_{12}} \right).$$

(6)

The normal component of the wind velocity vector $\bar{v}_n$ is expressed as $\bar{v}_n = \bar{c} \sin \theta$, and then the mean sound velocity is:
\[ \tau = \sqrt{(v \cos \theta)^2 + v_n^2}. \]  

The parallel component \( v_p \) is derived from a difference between bi-directional TOFs as follows:

\[ v_p = \frac{1}{2} \left( \frac{L}{t_{21}} - \frac{L}{t_{12}} \right). \]  

The \( v_n \) included in the previous equation is measured by another sound probe whose base line crosses the first base line at right angles. The \( v_n \) is expressed as follows:

\[ v_n = \frac{1}{2} \left( \frac{L}{t_{43}} - \frac{L}{t_{34}} \right), \]  

where \( t_{43} \) and \( t_{34} \) denote TOFs measured by the another sound probe. The wind velocity vector is derived from eqs. (8) and (9) as follows:

\[ \vec{v} = \sqrt{v_p^2 + v_n^2}, \]  

\[ \alpha = \tan^{-1} \left( \frac{v_n}{v_p} \right). \]

### 3. Field Experiment

Figure 3 shows the experimental layout in the field without the obstruction in the circumference. Four sensors shown in the symbol □ are installed in the four square tops of about 200 m² in area. Our present system measures the micrometeorological parameters of the total region whose height is 0.9 m above the grand. Conventional type ultrasonic thermometer and anemometer, for the reference measurement, shown in the symbol ◯ is set in the center of the measurement space. The reference equipment measures the micrometeorological parameters of the narrow region. Four acoustic sensors are connected with a personal computer (PC) (Celeron 466 MHz, 128 MB-RAM) through an analog to digital (A-D) and digital to analog (D-A) converter (DAQCard-6062E / National Instruments).

The measurement was performed from the local time of 13:40 to 14:40 GMT+09:00 in daytime with 20 s intervals. The sensors faced each other with 20 m long base lines. The base lines were intersected at the center point of the measurement space with right angles. The sensor consisted of one SP; a loud speaker (SD-9D4B/Clarion) with audio frequency range, and one MIC; a condenser microphone (CMS-64/BSE). The SP was fixed at the center of the sensor and the MIC was fixed at 85 mm above the SP. Since the sampling rate of the A-D / D-A converter was 125 kHz, the time resolution of the measurement was 8 µs. The probing sound was a down-chirp signal with a modulated frequency from 1.6 kHz to 5.6 kHz within 20 wavelengths. A sound pressure level of the probing sound was 50dB near the SP. The probing sound was launched 20 times during 4 s. the received signals were recorded and analyzed by the PC in real time. Then the averaged signal was used for the calculation of the TOF. Then, the micrometeorological parameters were measured from the TOFs in real time substantially. For reference, an ultrasonic thermometer-anemometer (TR-90AH WAT-395 / KAIJO) was installed near the center point of the measurement space at 0.9 m above the ground level.

### 4. Experimental Results and Discussions

Experimental results are shown in Fig. 4. The traces (a), (b) and (c) show the change of the air temperature, the wind velocity and the wind direction, respectively. The solid lines are the spatial mean values measured by the present system. The dashed lines are the values at one point measured by the conventional ultrasonic thermometer and anemometer as the reference. These time changes contain long periodic wave and short periodic wave. Two experimental results mutually agree well. Since the measurement space was open field without any obstruction, the wind velocity distribution could be nearly uniform. Furthermore, since the wind
promoted to the heat transfer, nearly uniform temperature distribution was formed. Therefore, that caused the agreement in the long periodic waves of the parameters. In short periodic ones, there were little differences between two changes. Since the reference measured the parameters at one point, then it was influenced easily by the local turbulence of the parameters. On the other hand, the method of region measurement by the system can acquire the parameters without the effect of the local turbulences.

5. Conclusions
The spatial mean values of air temperature, wind velocity and wind direction in about 200 m² field were nondestructively measured in real time by two pairs of the sound probe with 20 m long base line. The results showed that this method could effectively measure the spatial mean values of micrometeorological parameters in the open field. Furthermore, we need to verify the accuracy of the system by increasing the number of the references.

6. Acknowledgements
This work was supported in part by a Grant-in-Aid for Scientific Research (Exploratory Research) No. 14656094 from the Ministry of Education, Culture, Sports, Science and Technology, and in part by a 2003 Grant-in-Aid from the Society of Agricultural Structure, Japan.

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