Crosswind Velocity Measurement Using Ultrasonic Delay line

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1. Introduction

Sound probe with sound delay line is widely used to measure spatial temperature$^{[1-3]}$, distance$^{[4]}$, sound velocity$^{[5]}$ and wind velocity using character of non-contact and area measurement in various measurement fields. Conventional wind velocity measurement using sound method is based on detecting the difference between bidirectional velocities parallel to sound path on sound probe. In this method, the directional component normal to the sound path is considered to be an error factor$^{[6]}$. To realize an anemometer to measure crosswind velocity, which is normal to the sound path, we consider an ultrasonic delay line by simulation and experiment.

2. Principle of Measurement

Schematic diagram of crosswind velocity measurement using an ultrasonic delay line is shown in Fig. 1. An ultrasonic delay line in test section of a wind tunnel is set normal to the crosswind. The crosswind increases the traveling time of the ultrasonic delay line and the equivalent length of the sound path obtained from the time of flight (TOF). The sound transmitted from an ultrasonic speaker (SP) to $x$-direction reaches an ultrasonic microphone (MIC) under windless environment whereas the sound drifts down the wind under the crosswind. The sound appropriately directed as shown in Fig. 1 will only reaches the MIC under the crosswind where $c$ sound velocity, $L$ distance between the SP and MIC of the sound path, $TOF$ under no crosswind environment, $v$ velocity of crosswind, $f$ frequency of sound, $\Delta TOF$ and $\Delta L$ increase of $TOF$ and sound path respectively.

Crosswind, which has no $x$-directional component of velocity, is $v$ along $y$-axis. Sound path is $L(x,y)$. We have sound path equations as following:

\[
\frac{dx}{dt} = c \cos \theta, \quad (1)
\]

\[
\frac{dy}{dt} = c \sin \theta - v, \quad (2)
\]

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![Fig. 1 Schematic diagram of measurement.](image1)

![Fig. 2 Experimental setup.](image2)

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\begin{align*}
\text{Initial condition} & \quad L(x,y)\big|_{t=0} = L(0,0), \quad (3) \\
\text{Final condition} & \quad L(x,y)\big|_{t=TOF+\Delta TOF} = L(L,0), \quad (4) \\
\Delta TOF \quad \text{and} \quad \Delta \phi \quad \text{have relation as following equation} & \quad \Delta \phi = 2\pi f \Delta TOF, \quad (5)
\end{align*}
\]

The phase difference $\Delta \phi$ obtained from $\Delta TOF$ is calculated under the direction $\theta$ that satisfies above conditions.

3. Experiments

Figure 2 shows the experimental layout. We used a Goettingen type wind tunnel, which has maximum velocity of 20 m/s for continuous wind. Distance $L$ between SP and MIC is 465 mm. The center
Phase Difference $\Delta \phi$ (rad)

Wind Velocity $v$ (m/s)

Fig. 3 Numerical and experimental relationship between wind velocity $v$ and phase difference $\Delta \phi$ between the input and output signals of the ultrasonic delay line.

of the ultrasonic delay line is set 260 mm apart from air duct of wind tunnel (usable area 500×500mm$^2$) and 230 mm above from lower edge of the air duct. The SP and MIC (PT40-18, PR40-18/Nippon Ceramic) operate at the center frequency of 40 kHz. Function generator (NF1930A) and digital oscilloscope (HP54602B) are used for probing signal generator and phase comparator, respectively. Calibrated anemometer/thermometer (AM-09T/RION) is used for the reference.

The crosswind introduces the phase difference $\Delta \phi$ between the input and output signals of the ultrasonic delay line on calculation and experiment. Figure 3 shows the relationship between crosswind velocity $v$ and calculated or measured phase difference $\Delta \phi$ where $c$ is the sound velocity of 349 m/s for the calculation and experiment, $f$ is the sound frequency of 40 kHz. The solid line represents the calculation and the circles represent the experiment measured by the present system. Calculated and experimental results approximately agree with each other. The error between the results obtained by the calculation and the experiment was 4.4 % or less. The phase delay is second order function of the crosswind velocity.

Nevertheless complete countermeasures for the reflection of continuous wave in measurement are required, we used continuous ultrasonic waves for experiments. As far as pulse wave is used for measurement, sampling rate restricts the resolution in time domain. A method to detect the phase difference by means of continuous waves makes the resolution in time domain more precise and more accurate than the pulse wave detection method.

4. Conclusion

In conventional method to measure wind velocity, the directional component parallel to the sound path is measured and the component normal to the sound path is considered to be an error factor because a crosswind affects phase difference $\Delta \phi$ and $\Delta \text{TOF}$ on the sound path. In contrast, we tried to measure the crosswind velocity by the phase difference of the sound path.

The crosswind introduces phase difference $\Delta \phi$ between the input and output signals of the ultrasonic delay line on calculation and experiment. The phase difference $\Delta \phi$ and $\Delta \text{TOF}$ in the crosswind environment were calculated and measured. The error between the data of calculation and experiment was 4.4 % or less.

We described a new ultrasonic measurement principle and a measurement system, which has the advantage that it can be used for the applications such as crosswind velocity sensors for air ducts of building air conditioning system or for air tubes of factory. The crosswind-type sensor proposed here does not affect the flow because the transducers are only set aside of the flow.

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References