WIND SPEED AND DIRECTION MEASUREMENT WITH NARROWBAND ULTRASONIC SENSORS USING DUAL FREQUENCIES

H.Inaki Schlaberg**, Yan Liu, Zhihong Li, Shi Liu

School of Control and Computer Engineering, North China Electric Power University, Beijing,102206, China
email: h.i.schlaberg@ieee.org

Keywords: ultrasound, wind speed, wind direction, measurement

Abstract

Knowing the wind speed and direction in an electrical power generating wind farm is an important factor in its management. A measuring device for this function with no moving parts is desirable to reduce maintenance due to wear of the mechanical parts. Ultrasonic measuring techniques can be employed in such a device to fulfill this requirement by measuring the time it takes for a signal to propagate from an emitter to a receiver sensor. Wind in the direction of the sound wave, or against it will affect the travel time of the sound wave and the wind speed can be extracted from these Time Of Flight (TOF) measurements. Commonly used narrowband ultrasonic transducers have the disadvantage of generating a long oscillating signal where the start of the received signal has a very small amplitude and cannot be directly detected and flagged with a simple threshold circuit. The present paper describes a method where two signal bursts of different frequencies within the bandwidth of the transducers are used to obtain the TOF. The phase difference between the emitted and the received signal is measured at two frequencies and the results are then combined to give the TOF. The wind direction can be obtained with an additional measurement in the orthogonal direction by a second pair of sensors.

1 Introduction

To measure wind velocity with ultrasound, the time it takes for a transmitted signal to reach a receiver is measured. Knowing the distance between the emitter and receiver, the velocity of sound can be calculated. If there is wind in the direction of the direction of the transmitted signal the velocity with which the signal propagates will the sum of the speed of sound in the air plus the speed of sound of the wind. If the wind is in the direction opposite to the sound signal the effective velocity will that of the speed of sound in air minus the velocity of the wind. See Figure 1.

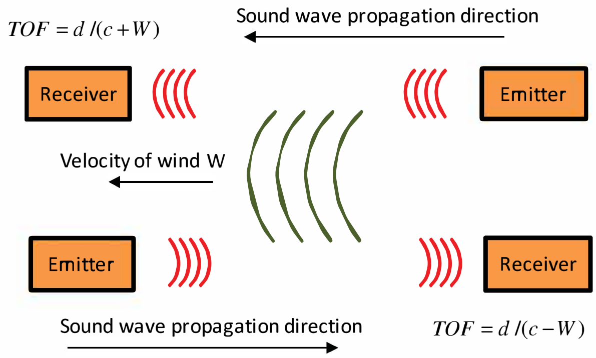

Figure 1: Effect of wind speed in the same and opposite directions as the sound propagation on the TOF.

When the wind is not directly aligned with the sensors, only the component of the wind in the direction of the transmitted sound will contribute to the change in the arrival time of the sound signal, as is shown in Figure 2.

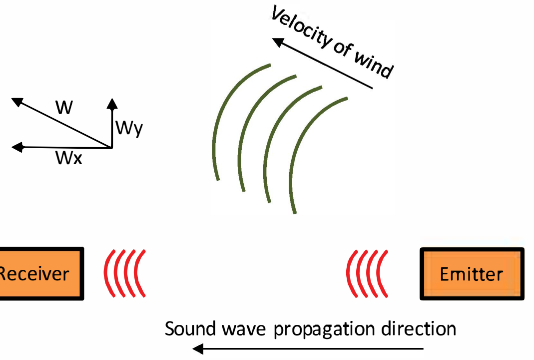

Figure 2: When the wind is not aligned with the sound propagation path its effect is decomposed into its vector components

Thus using a second pair of transducers at a right angle of the first pair the x and y components of the wind velocity can be determined as it will influence the arrival time of the sound signals differently depending on its direction. See Figure 3. The tangent of the wind direction angle will be quotient of the y and x components.

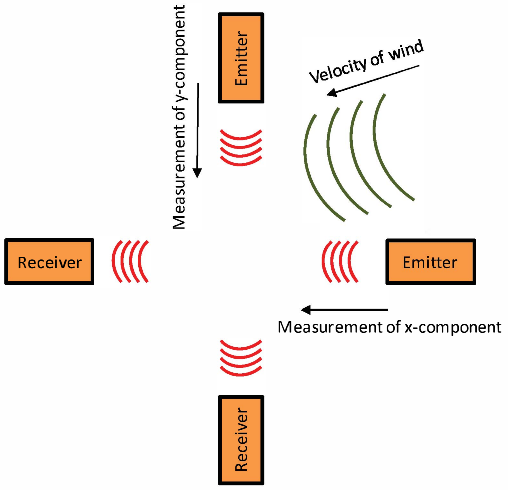

Figure 3: With two orthogonal measurements the x and y components of the wind can be extracted and thus the angle of the wind direction is determined

The velocity of sound in air is dependent on the temperature of the air by the following relationship:

$$c = \sqrt{\frac{T}{273.15} + 1} \tag{1}$$

This would imply that the temperature needs to be measured to provide an accurate value of the wind speed. However making two measurements of the TOF in opposite directions can determine the velocity of sound of the medium, which is temperature dependent, and the velocity of the wind separately. Consequently, the temperature of the air can be determined with the measurements, which is a useful parameter to have in an environment where meteorological variables such as wind speed and direction are measured.

The time it takes for a signal to propagate in the direction of the wind, t_F and against the wind t_B is given by the following expressions:

$$t_F = \frac{d}{c+W} \qquad t_B = \frac{d}{c-W} \tag{2}$$

where d is the distance between the sensors, c is the velocity of sound in the air and W is the velocity of the wind.

From here the wind velocity W, the sound velocity in the medium, c, and the temperature T can be calculated as follows:

$$W = \frac{d}{2}\left(\frac{1}{t_F} - \frac{1}{t_B}\right) \qquad c = \frac{d}{2}\left(\frac{1}{t_F} + \frac{1}{t_B}\right) \qquad T = 273.15\left(\left(\frac{c}{331.45}\right)^2 - 1\right) \tag{3}$$

2 Measurement principle of TOF and problem with narrow band sensors

The TOF is the time it takes for the ultrasound signal from leaving the emitter to reaching the receiver. In the simplest case, the received signal is detected when the voltage at the receiver exceeds a certain threshold value that lies just above the noise floor and can be implemented with a comparator. The output of the comparator can then be used to stop a timer, interrupt a processor or activate another method of measuring the time between sending the emitter signal and observing the signal at the receiver.

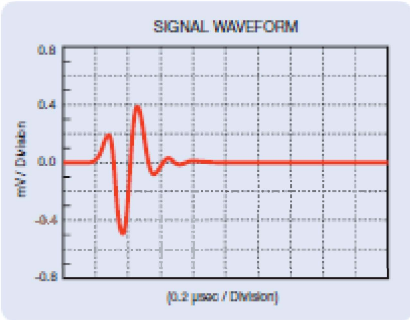

Figure 4: The clear signal of a typical commercial transducer in a liquid

Ultrasound transducers used in liquids usually have a relatively wide band width and the signals generated are short as can be seen in the typical example of a commercial transducer shown in Figure 4. Piezoelectric ultrasound transducers for use in air on the other hand, tend to have a long ringing period after the initial activation pulses. One of the causes for this is the large acoustic impedance difference between the piezoelectric material and the air, causing the signal to bounce back and forth inside the material. A typical signal from such a transducer can be seen in Figure 5 where the excitation signal was a burst of 10 cycles of a sine wave at 40kHz with a pair of transducers separated by about 500mm.

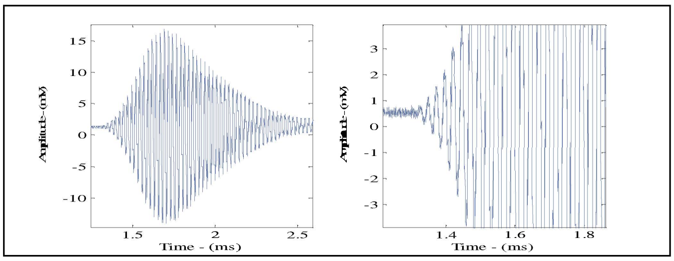

Figure 5: Typical signal from a narrow band air transducer and the detail of the initial wave cycles

The right part of Figure 5 shows an amplified version of the left side. Here the start of the received pulse can be observed in more detail. The first few oscillations are very small in amplitude and actually the very beginning appears to be within the noise of the signal. The signal in the figure has actually been averaged four times to reduce to effects of the noise, however parts of the signal still appear within the amplitude of the noise floor.

This effect makes the accurate determination of the TOF not possible by just using a simple threshold level.

3 Phase comparison method

An alternative method based on phase comparison that has been employed in distance measurements [1] and temperature measurements [2,3] can also be applied to the determination of wind speed and direction.

Without wind and at a constant temperature the speed of sound in the air and the TOF will remain unchanged during consecutive measurements. While the exact arrival time cannot be determined from looking at beginning of the received signal, it can be calculated from looking at the phase difference between the emitted and received signal in a region where the amplitude is large. If the frequency is constant, the phase difference will be constant at any part of the wave for a given temperature and distance between the sensors.

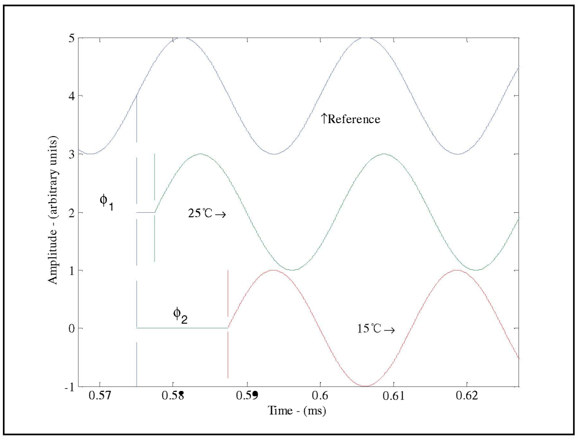

Figure 6: The different arrival times due to temperature changes produce phase differences with the original signal that have different values. The emitter and receiver are separated by 200mm and operate at 40kHz

Figure 6 shows that at a temperature of 25C the emitted and received signals have a certain phase difference between them. At 15C the speed of sound is somewhat slower and the signal will take a little longer to arrive. This will result in a different phase angle between the emitted and received signal.

Looking at the phase changes for wind speeds up to 50 m/s in either direction, at a constant temperature of 25C and with the sensors 200 mm apart, the graph in Figure 8 is obtained. Here again there are several wind speeds that correspond to the same phase value and the actual wind speed cannot be determined from the measurement.

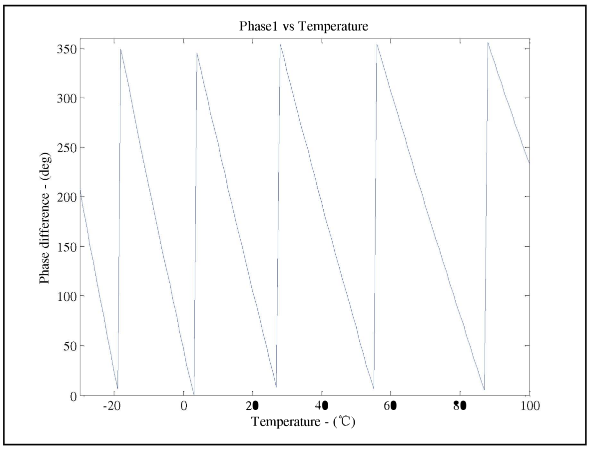

Figure 7: Phase values of the received signal when the temperature changes between -30C and 100C

Figure 7 shows the phase difference for temperatures that could be typical for locations where wind farms might be deployed i.e. -30C to 100C, using a distance of 200 mm between the sensors and a frequency of 40 kHz. The phase difference changes between 0 and 360 degrees, however the same phase value occurs several times, creating an ambiguity as to which temperature segment a particular value would correspond. If the temperature range would only be considered between 0C and 25C, for example, this ambiguity would not occur.

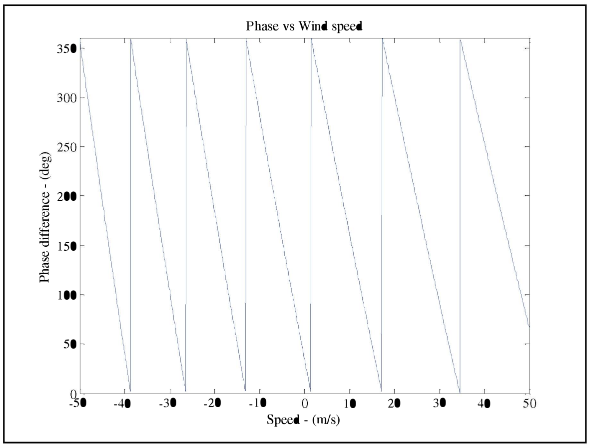

Figure 8: Change in the arrival phase for wind changes from -50m/s to +50m/s at a temperature of 25C and a sensor distance of 200mm and operating at 40kHz

4 The use of dual frequencies

This problem can be overcome by using a second measurement with a different frequency. The signal with a different frequency will have a different wavelength and therefore the number of whole wavelengths that fit between the sensors will differ. The remainder of dividing the distance by the wavelength would be the phase angle and so depends on the frequency. The second frequency has to be within the bandwidth that the transducers can produce and therefore will only be slightly different from the first frequency. Using the difference between the phases of the two frequencies a unique value of temperature or wind velocity can be determined.

The method can be explained as follows. The distance between the emitter and receiver is fixed, d, in our case 200mm. This distance can fit a full number of wavelengths, n, and the remainder is the phase of the received signal. For two frequencies, f1 and f2, the relationships are:

$$d = \lambda_1(n_1 + \phi_1) \text{ ; } d = \lambda_2(n_2 + \phi_2) \qquad (4)$$

where

$$\lambda_1 = c / f_1 \text{ ; } \lambda_2 = c / f_2 \qquad (5)$$

With c being the velocity of sound, f the frequency, λ the wavelength, Φ the phase (with a range from zero to one), n the number of whole waves that fit into d, the distance. The subindicies refer to the two frequencies.

Combining the expressions yields:

$$\frac{d}{c}\Delta f = \Delta n + \Delta\phi \qquad (6)$$

Δ n can be either 0 or 1 depending on which of the two phases is ahead and its value can be incorporated into ΔΦ using the following expressions [3]:

$$\begin{cases} \phi_1 > \phi_2, \Delta\phi = \phi_1 - \phi_2 \\ \phi_2 \geq \phi_1, \Delta\phi = \phi_1 - \phi_2 + 1 \end{cases} \qquad (7)$$

The TOF can now be calculated from:

$$TOF = \frac{d}{c} = \frac{\Delta\phi}{\Delta f} \qquad (8)$$

Figure 9 shows the phases for frequencies of 41 kHz and 40 kHz and the phase difference according to the above equations when the wind over the whole 200 mm ring is experiencing the variations from -50ms to +50m/s. While the individual phase values wrap around many times, the difference value has no phase ambiguity in the selected range. The phase values have been converted from the zero to one range to a 0 to 360 degree range, but could also be set into the 0 to 2π range when multiplying by the appropriate factor.

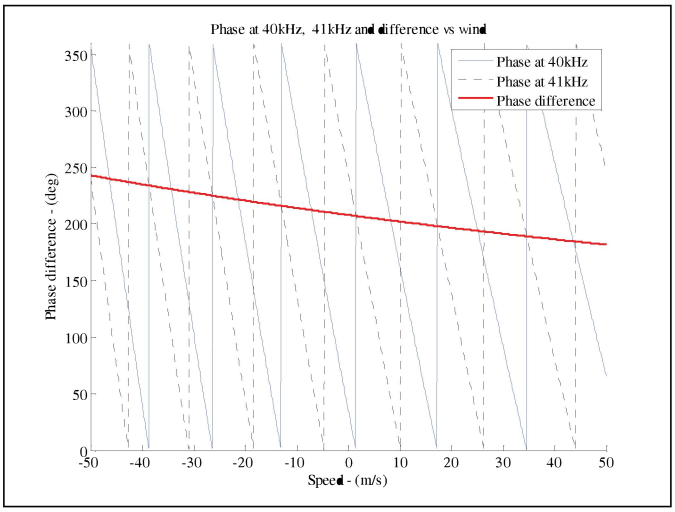

Figure 9: Phase values at 40kHz, 41kHz and the difference between them when the wind speed varies from -50m/s to +50m/s while the temperature is 25C and the distance between the sensors is 200mm.

5 Conclusions

The paper has presented a method for measuring wind speed and direction using narrow band ultrasound transducers by employing dual frequencies. Measuring the phase in a part of the wave where the amplitude is large overcomes the difficulties of measuring the arrival time when the start of the arriving signal is very small and of the same level as the noise.

6 References

[1] S. S.Huang, C. F.Huang, K. N.Huang, M. S.Young, "A high accuracy ultrasonic distance measurement system using binary frequency shift-keyed signal and phase detection", Review of Scientific Instruments, Volume 73, Issue 10, 3671-3677 (2002)

[2] H.I. Schlaberg, S. Liu, Z. Li, "Flame tomography based on phase comparison using dual ultrasonic frequencies", 4th Asian Joint Workshop on Thermophysics and Fluid Science, Busan, Korea (2012)

[3] W.Y.Tsai, C.F.Huang, T.L.Liao, "New implementation of high-precision and instant-response air thermometer by ultrasonic sensors", Sensors and Actuators A 117, 88–94 (2005)