ELEC5882M Final Report

Slipstream Detection using Ultrasonic Anemometer

SHARAD BHOWMICK

Student ID: 201376731

Submitted in accordance with the requirements for the degree of
Master of Science
in
ELECTRICAL ENGINEERING AND RENEWABLE ENERGY SYSTEMS

Supervisor: Mr. ROLAND G. CLARKE

Assessor: Mr. David Moore

The University of Leeds

School of Electronic and Electrical Engineering

August 2020

Declaration of Academic Integrity

The candidate confirms that the work submitted is his/her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated in the report. The candidate confirms that appropriate credit has been given within the report where reference has been made to the work of others.

This copy has been supplied on the understanding that no quotation from the report may be published without proper acknowledgement. The candidate, however, confirms his/her consent to the University of Leeds copying and distributing all or part of this work in any forms and using third parties, who might be outside the University, to monitor breaches of regulations, to verify whether this work contains plagiarized material, and for quality assurance purposes.

The candidate confirms that the details of any mitigating circumstances have been submitted to the Student Support Office at the School of Electronic and Electrical Engineering, at the University of Leeds.

SHARAD BHOWMICK
Date: 03/September/2020

Slipstream Detection using Ultrasonic Anemometer

Sharad Bhowmick
School of Electrical and Electronics Engineering
University of Leeds
Leeds, U.K.
el19sb@leeds.ac.uk

***Abstract*— In this project a 2-Dimensional sonic anemometer is being developed to find the slipstream region created by a vehicle going ahead. Air drag in a vehicle causes up to one third of loss in momentum in a vehicle. The air drag in a moving vehicle can be minimized by utilizing the slipstream region caused by the movement of other vehicles which can improve the overall fuel efficiency of the vehicle.**

A sonic anemometer uses ultrasonic waves to detect the wind speed. By measuring air speed in two direction separated by right angle, the direction as well as speed of wind can be precisely calculated. In this paper air velocity is used for finding the slipstream by using continuous sonic wave using dual frequency technique. The 2-D wind velocity can be calculated using vector measurement that will help the driver to maintain his vehicle inside the slipstream region which will reduce the fuel consumption of the vehicle. This method will be extremely efficient in self-driving vehicles.

Keywords*— *Slipstream, Time of flight, ultrasonic, anemometer.

I. Introduction

Slipstream is a low-density region behind any moving object, the relative density of fluid in this region is lower than that of the surrounding region. A slipstream region created by a vehicle has lower air pressure compared to the surrounding region. Slipstream region's shape and dimension depends on the shape and size of the vehicle and its movement velocity relative to wind. Larger vehicles such as trucks and Lorries creates a larger slipstream region compared to a family car. Maintaining the car inside this region improves the fuel efficiency by reducing the air drag on the vehicle. This technique is also called drafting.

In nature animals have been seen drafting, school of fishes utilise it to conserve their energy whereas birds use similar technique known as vortex surfing to increase lift thus saving energy while flying. . In reference [1], the researchers discusses how small and weaker fish swims behind the faster fish in order to conserve the energy, also the tail movement of fishes swimming behind was lower than their other counterparts, at lower speed of just 1 kmph, the fishes conserves up to 12% of their energy. The energy conservation increases with higher speeds. Cyclists and runners also uses slipstreaming to reduce their energy consumption and in motorsports, drivers utilise the slipstreaming to gain advantage over their opponents. Studies have shown that drafting may save up to 30% of the total fuel consumption.

In this technique, the body moving ahead faces the max air drag and opens up a pocket of low-density region called as slipstream region, thus the vehicles moving just behind in that region experience lesser air drag.

In future where autonomous and connected vehicles will replace our manually controlled vehicles, tailgating and other hypermiling techniques won't pose any threat as Vehicle to vehicle V2V communication and Vehicle to everything V2X communication protocols will keep the vehicle connected thus reducing the stopping time syncing the movement of vehicle thus bringing down the required gaps between two moving vehicle smaller, thus safely utilizing this technique more efficiently.

II. Selection of anemometer Technology

Anemometers detects the wind speed by measuring various physical characteristics of the wind.

A. *Anemometer Based on Wind velocity and kinetic energy of wind*

Mechanical anemometers utilize the kinetic energy of the wind in order to move a cup, wheel, propeller, etc. to analyse air speed. Moving parts in these types of anemometer require regular maintenance and these are less sensitive to decreasing speed and thus tend to overestimate the air speed due to the gust of wind [2]. These factors make the device unsuitable for our operation.

B. *Anemometers based on the wind pressure*

Anemometer which are based on wind pressure such as pitot tube, plate anemometer, etc. are extremely sensitive to change in temperature, barometric pressure and their low efficiency at slow air velocity makes them unsuitable for this project.

C. *Anemometers based on the wind's property of transmitting wave*

Laser Doppler anemometers uses a technique called Doppler effect which causes the increase or decrease in the frequency of sound wave with change in the relative position of the observer. Although the method can give very accurate results but this technology is expensive and cannot be employed without using tracer particle [3].

D. *Sonic anemometers*

Sonic anemometers use ultrasonic sonic waves, they comprise of a pair of ultrasonic transducers which act as a transmitter and a receiver. The transmitter produces a sonic pulse which is detected by the receiver placed in the opposite side, the sonic waves travel faster in the direction of the air flow and slower in the direction against it [4].

Sonic Anemometers have no moving parts, they can also be used to measure both slow and fast air movement and have higher resolution than most other types of anemometer due to their high frequency operation. The sonic anemometer are highly accurate even in close proximity of objects such as vehicle's body in our case which can reduce sensitivity of other types of anemometer, its measurement is independent of flow property which includes spatial and time variations due to medium density, temperature, humidity, etc. as discussed in [5]. Reference [6] describes that sonic anemometer are the most suitable type of anemometers to measure turbulent flow. The stated factors make sonic anemometers most suitable for this project.

III. SONIC ANEMOMETER AND IT'S WORKING

Sonic anemometers are classified in 2 categories, continuous phase sonic anemometer which is also called an indirect method and pulsed sonic anemometer also known as direct method [5]. The speed of sound (c) is affected by the temperature and density of the medium. The relationship of speed of sound is given by the Boyle's law [7]. The equation is given as:

$$c = \sqrt{\mathrm{RT}\gamma/M} \tag{1}$$

Here, c is the speed of sound, R is the universal gas constant, T is the absolute temperature (in kelvin), γ is the ratio of specific heats and M denotes the Molar mass.

A. *Pulse sonic anemometer*

In a pulse sonic anemometer, sonic pulses are transmitted in one direction and the transducer's roles are reversed and then the pulses are sent to the opposite direction in the same axis of measurement. e.g. In Figure 1, in the first step, transceiver 1 and transceiver 2 act as a transmitter and receiver respectively and in next step the role is reversed. Pulses travelling against wind arrive later than those travelling in the direction of the wind. Thus time of flight calculation of both direction help us calculate the speed of air.

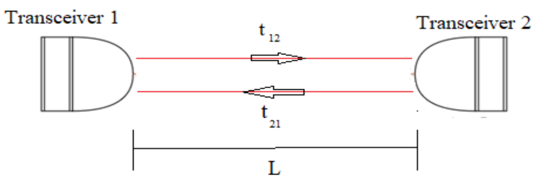

Figure 1 Layout of transceiver

Time of Flight (TOF) is defined as the time taken by the sound wave to reach from the transmitter to the receiver. The speed of air affects the TOF and a time lag is introduced to the sound wave if the wind is flowing in the opposite direction of sonic wave whereas in the case of same direction wind flow the time taken by sound wave is lower than the reference time in the same medium. The time taken also depends on factors such as distance between the transducer medium of transmission, humidity and temperature. Reference [9] describes that the TOF is given by the following equation:

$$T_{\mathrm{TOF}} = L/(c \pm v) \tag{2}$$

Here, T_{TOF} denotes the time of flight, L is the distance between the two transducers, c is the speed of sound and v is the air speed along the transducer's axis. The c depends on other factors such as temperature, density, etc., as described in (1). $L/(c+v)$ denotes the tof in the direction of wind and $L/(c-v)$ gives the tof against the direction of wind

B. *Continuous phase anemometer*

In a continuous phase anemometer, the transmitter sends a continuous wave of sonic energy which is compared with the reference wave, the drawback of this technique is that since the medium of transmission affects the transmission properties of sound waves factors such as relative humidity, temperature, etc. affects the data and therefore should be known to get accurate results. To overcome this problem phase shift method (PSM) can be used. Using PSM, speed of sound and air velocity can be calculated by keeping the distance of the transducers constant. The variances or noises in phase shift caused by environmental noises and electronic noises cancels out each other. This can be done by employing a phase data detector to compare received signal with reference to it's transmitted signal as discussed in [8].

If a transmitter is fed with a continuous signal, at receiver the signal can be written as $V(t) = A\sin(\omega t + \varphi)$, here A denotes peak value of received signal, ω is the resonant angular frequency and φ denotes the phase shift. φ is directly proportional to the distance. A phase ambiguity will occur if the distance between the transducers exceeds the full wavelength of frequency. The wavelength (λ) of 40kHz transducer at $20°C$ is:

$$\lambda = V_{20°}/f = 0.8575cm.$$

Here, λ = wavelength, $V_{20°}$ = Velocity of sound at $20°C$ (340m/s) and f=frequency (40kHz).

The distance is extremely short for our application therefore to overcome this problem we will use a technique where two different phase shifts of different frequency signals will be compared which will allow us to increase the distance between the two transducers, more than the wavelength

IV. METHOD

The dual frequency continuous wave time of flight method is derived from combining the single frequency continuous wave method and time of flight method.

Figure 1 represents the two ultrasonic transceivers facing each other. In [7] and [8] the authors have used the below discussed dual frequency technique to find the temperature of a system and distance respectively. Equations (3)-(6) are inspired from the two papers. The first frequency (f_1) and second frequency (f_2) are continuous waves which are transmitted from the same transmitter one after another with a pre-determined time interval. The first phase shift (φ_1) and second phase shift (φ_2) are caused due to f_1 and f_2 respectively. Each respective phase shifts are calculated after the transmission, reception and computation of frequency f_1 and f_2 are completed. Same procedure is repeated with interchanging the operations of the transducers, i.e. the transmitter and receiver in the first step now acts as receiver and transmitter respectively. When the distance between both transducers L is fixed and known, comparison of both phase shift allows the calculation of air velocity c. Reference [7] describe the formula for each frequency which is given by:

$$n_1 + \varphi_1/2\pi = L * f_1/c \tag{3}$$

$$n_2 + \varphi_2/2\pi = L * f_2/c \tag{4}$$

Here n_1 and n_2 are integers, φ_1 and φ_2 are phase shift of frequency f_1 and f_1 respectively. L denotes the distance between the transducers which is constant and c represents the speed of sound.

Integer n_1 and n_2 can have only two possible values i.e. $n_1 = n_2$ or $n_1 = n_2 + 1$. So, the value of phase shifts can be written by the following algorithm:

- when $\varphi_1 > \varphi_2$,

$$\Delta\varphi = \varphi_2 - \varphi_1 \quad (5)$$

- when $\varphi_1 < \varphi_2$,

$$\Delta\varphi = \varphi_1 + 2\pi - \varphi_2 \quad (6)$$

Here,

$$\Delta f = f_2 - f_1 \quad (7)$$
$$\Delta n = n_2 - n_1 \quad (8)$$

Since $\Delta n\ is\ sufficiently\ small$ in our operations we can consider $n_1 = n_2$ which will make (7) non-existent.

$$\omega_1 = 2\pi f_1 \quad (9)$$
$$\omega_2 = 2\pi f_2 \quad (10)$$
$$\Delta\omega = \omega_2 - \omega_1 \quad (11)$$

The phase shift difference $\Delta\varphi$ can be used to determine the ultrasonic velocity and therefore the air velocity if the maximum fluctuation does not exceed one wavelength or complete period of difference of frequency Δf. If it exceeds then phase ambiguity will occur. The range and resolution of the sonic anemometer depends on the frequency f_1 and f_2 selected.

For our system we are taking $f_1 = 38Hz$ and $f_2 = 40kHz$, then $\Delta f = f_2 - f_1 = 2kHz$ so $\Delta n + \Delta\varphi/2\pi$ becomes $2000/c$.

Time of Flight is given by:

$$T_{\text{TOF}} = \frac{\Delta\varphi}{\Delta\omega} = \frac{f_2 - f_1}{\omega_2 - \omega_1} \quad (12)$$

From 12 we get:

$$\Delta\omega * T_{\text{TOF}} = \Delta\varphi \quad (13)$$

From 13 we get

$$\omega_1 * T_{\text{TOF}}{}^{+} = \varphi_1^{+} \quad (14)$$
$$\omega_2 * T_{\text{TOF}}{}^{-} = \varphi_2^{-} \quad (15)$$

Here, T_{TOF}^{+} is the tof in the direction of wind, T_{TOF}^{-} is the tof against the direction of wind, φ_2^{+} denotes the phase along the wind and φ_2^{-} denotes the phase against wind direction.

The above method is a narrow bandwidth technique which measures the air speed by the following steps:

- First frequency f_1 is generated by the IC555 timer and first phase shift φ_1 is calculated by comparing the received signal from the transmitted signal by using equation. Since the length between the transducers is constant therefore we know the length L, values for tof along the wind $T_{\text{TOF}}{}^{+}$ and tof against the $T_{\text{TOF}}{}^{-}$ are computed by the controller and known. The value of $\Delta\omega$ is a known constant. $\Delta\varphi^{+}$ and $\Delta\varphi^{-}$ is calculated by (14) and (15).

- Similarly second frequency f_2 is generated by the IC555 timer and the above calculations are performed and values w.r.t f_2 are obtained. All the data are substituted in (2) and the the velocity of air $\boldsymbol{v}$ **is** computed**.**

V. Simulation and Hardware

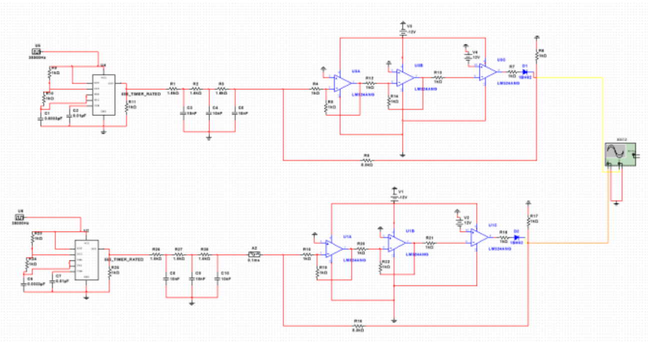

Figure 2 Simulation diagram made in Simulink

The simulation has an ultrasonic transmitter, square wave to sine wave converter ultrasonic receiver and amplification circuit as shown in Figure 2.

The ultrasonic transmitter is made by using an IC555 timer working as a a-stable multivibrator. The multivibrator is fed with a digital clock connected across the VCC and RST pin of the IC555 timer. The digital clock is configured to give a signal of 40 kHz or 38 kHz to the IC555 timer thus driving it to produce a square wave of 40 kHz or 38 kHz frequency respectively. The output from the transmitter which is a square wave is shown in the Figure 3. The clock frequency is set to give a signal of 38kHz for this situation. The time of one period of the wave can be calculated by $T = 1/f$ where T is the (time in sec) and f denotes the frequency in hertz. $T_2 - T_1$ in the figure gives us the time of 1 period which is 26.32 us, verifying that the transmitter is producing a 38 kHz output.

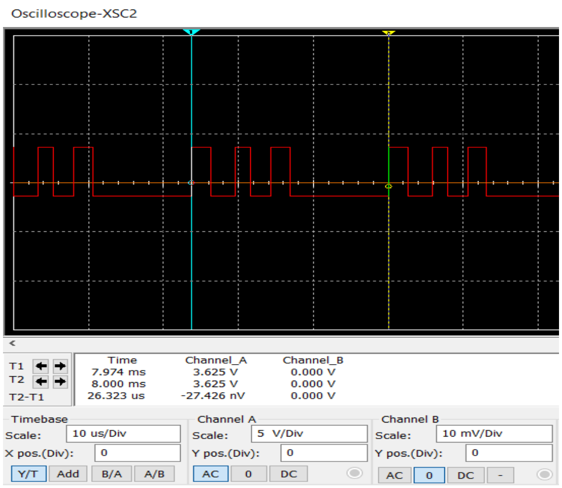

Figure 3 Output from ultrasonic transmitter

The square wave from the transmitter is fed to a sine wave generator. A three staged RC circuit is used to convert the square wave from the transmitter and a sinusoidal output is obtained. Figure 4 compares the output of the 3 stage RC circuit with the square wave output from the transmitter. It works in 3 stages, first the square wave is passed through first set of capacitor and resistor circuit, the input wave is converts into a parabolic shaped exponential wave, at the second RC circuit, the wave is filtered and appears like a triangular waveform and the final RC pair converts the triangular wave to a more curved sine wave. We can increase the number of RC pairs to make it more sinusoidal.

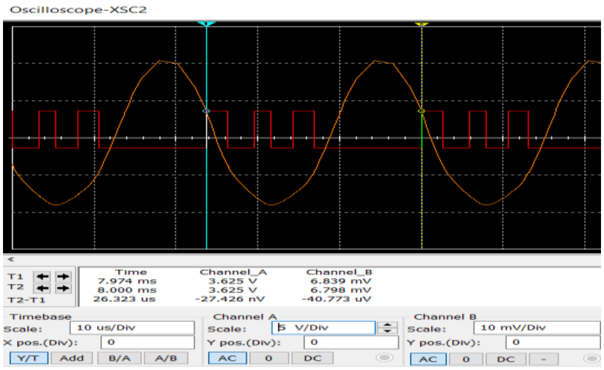

Figure 5 Comparison of sine wave output from the 3 stage RC sine wave generator to with the square wave output from the IC555 timer

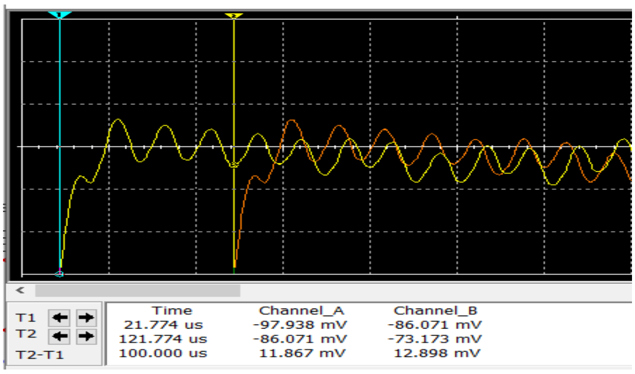

Figure 4 The yellow color depicts the normal output and the red line denotes the delayed output by the delay component

The signal from the transmitter is fed into the delay component which mimics the Time of Flight i.e. the time required for the ultrasonic signal from transmitter to reach the receiver. Figure 5 shows the working of a delay component. The delay of 0.1ms sec is fed in the delay component and the output of the oscilloscope shows that the signal with a delay component has a delay of 0.1s compared to the original signal.

The receiver circuit in the simulation have three Op-amp working as amplifier. The incoming signal from the delay component is passed through a non-inverting amplifier built using LM324ANG Op-amp. Gain of the amplifiers are controlled by the feedback resistors which is connected to the output of amplifier's inverting terminal. Three stage amplification is done to get an optimum amplification.

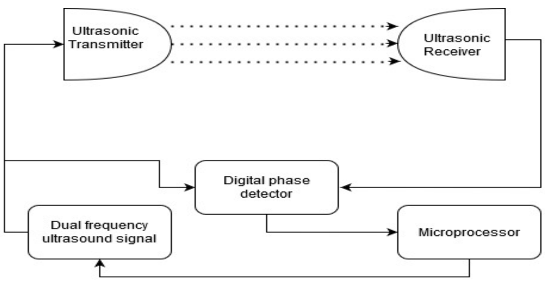

Figure 6 Block diagram of system

As shown in Figure7, the system will have 4 major components. A dual frequency generator will generate dual frequency of 38kHz and 40kHz. The digital phase detector will be connected to both the frequency generator and the receiver. Digital phase detector will compare the two phases to measure the phase shift. The ultrasonic receiver will have an amplifying circuit to amplify the incoming signal and an auto gain amplifier. Autogain amplifier will change the gain of the amplification to reduce the acoustic attenuation due to the varying ultrasonic signal.

VI. 2-DIMENSIONAL ANEMOMETER

A 2-axis anemometer also known as 2-D anemometer can measure the speed as well as the direction of air flow. It can be made by combining 2 pairs of single axis anemometers perpendicular to each other as depicted in Figure 8. The 4 ultrasonic transducers are mostly placed at 4 corners of an imaginary square (for simplicity we are keeping them at 4 cardinal directions i.e. in East, West, North and South).

The data is taken from both the east-west pair and north-south pair and the rectangular components of winds are computed to find the resultant direction and magnitude of wind.

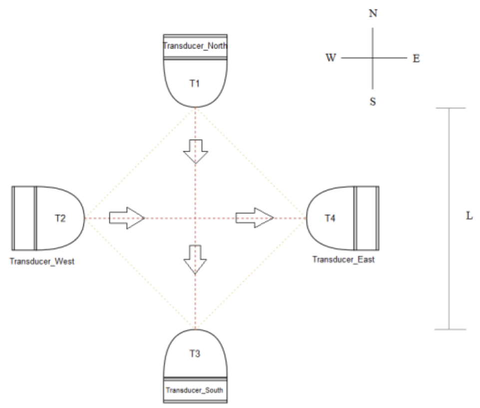

Figure 7 Ultrasonic transducer layout

A. Equations for finding the 2-Dimensional components

As discussed earlier, air speed is measured in two different direction using two different pairs of ultrasonic transducers. The first pair is along the north-south direction measuring the vertical component (v_y) of wind and another pair which is placed along the east-west direction measures the horizontal component (v_x)of the wind. Reference [10] discusses the method of calculating the direction of the wind, which can be accurately determined by calculating the wind speed in both horizontal and vertical directions and using the below formula:

$$\boldsymbol{v_y = \frac{1}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right)} \qquad \textbf{(16)}$$

$$\boldsymbol{v_x = \frac{1}{2}\left(\frac{1}{t_3} - \frac{1}{t_4}\right)} \qquad \textbf{(17)}$$

Here,

v_y = velocity of wind in North – South direction

v_x = velocity of wind in East – West direction

t_1 denotes the tof when north transducer act as transmitter and south as a receiver

t_2 denotes the tof when roles are reversed and north transducer act as receiver and south as a transmitter.

t_3 denotes the tof when east transducer act as transmitter and west as a receiver

t_4 denotes the tof when roles are reversed and east transducer act as receiver and west as a transmitter.

Taking vector components

$$\text{Magnitude}|\vec{V}| = \sqrt{(v_y^2 + v_x^2)} \quad (18)$$

$$\text{Direction of wind } (\overrightarrow{V}) = tan\,\theta = (\frac{v_y}{v_x}) \quad (19)$$

$$\theta = \tan^{-1}(\frac{v_y}{v_x}) \quad (20)$$

Rectangular components from magnitude $|\vec{V}|$ and direction θ

$$(|\vec{V}|cos\theta\ ,\ \ |\vec{V}|sin\ \theta)$$

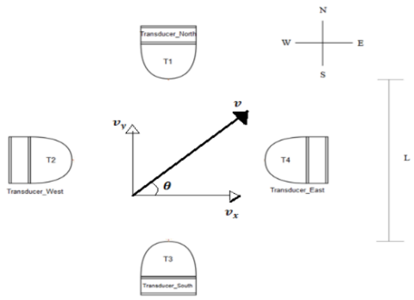

Figure 8 The visual representation of components of wind denoted by v_x and v_y vectors and resultant wind vector denoted by v.

VII. Flow Diagram

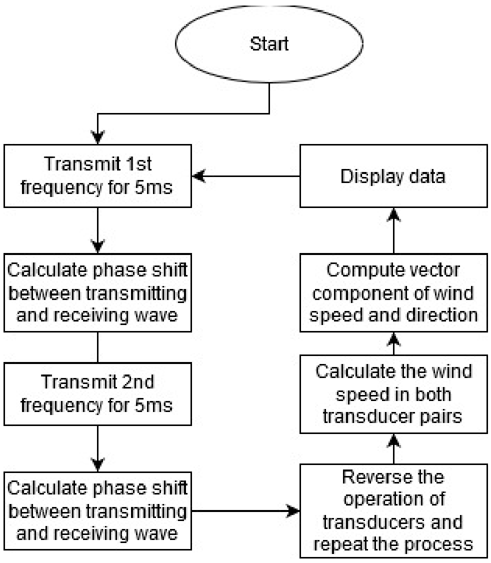

Figure 9 Flow diagram of proposed methodology

The above flow diagram shows us the working of the anemometer. The system starts by transmitting the first frequency for the first 5 ms. After 5 ms the second frequency is generated by the frequency generator. For first 5ms the phases for both receiver and transmitter are compared simultaneously for the first frequency and phase difference is found.

The transceivers switch their operations and now the transmitter in the previous cycle operates as a receiver and the receiver act as a transmitter.

Using the above data in (2) and (1) we get the speed of wind in one dimension from both the north-south pair and east-west pair. The resultant vector is calculated using (18) and (19). The wind speed and direction are displayed on the screen and the process works on a continuous loop.

VIII. Worked Out Example

Suppose a car is travelling at a speed of 60 kmph, due to a truck moving ahead of the car, the speed of air in the slipstream zone is 15 kmph. The distance between the two transducers L is 10 cm. The two frequencies are $f_1 =$ 38 kHz and $f_2 = 40$ kHz respectively.

Solution.

distance between the transducers $L = 10\text{ cm} = 0.1\text{ m}$

slipstream wind speed (v) = 15 kmph= 4.1667 m/s

Speed of sound (at 20°) $c = 343\text{ m/s}$

From (2)

$$T_{\text{TOF}} = L/(c \pm v)$$

Substituting all the values in equation (2):

$$T_{\text{TOF}} = 0.1/(343 \pm 4.1667)$$

$$T_{\text{TOF}}{}^{+}(along\ the\ wind) = 0.288\text{ ms}$$

$$T_{\text{TOF}}{}^{-}(against\ the\ wind) = 0.295\text{ ms}$$

From (9) and (10):

$$\omega_1 = 2\pi f_1 = 2\pi * 38000 = 238761.0417\text{ rad/s}$$

$$\omega_2 = 2\pi f_2 = 2\pi * 40000 = 251327.4123\text{ rad/s}$$

From (11), we have

$$\Delta\omega = \omega_2 - \omega_1 = 12566.3706$$

Calculating phase

For ω_1

$$\varphi_{\omega_1}^{+} = \omega_1 * T_{\text{TOF}}{}^{+} = 72.382\text{ rad}$$

$$\varphi_{\omega_1}^{-} = \omega_1 * T_{TOF}{}^{-} = 74.141\text{ rad}$$

For ω_2

$$\varphi_{\omega_2}^{+} = \omega_2 * T_{\text{TOF}}{}^{+} = 68.763\text{ rad}$$

$$\varphi_{\omega_2}^{-} = \omega_2 * T_{\text{TOF}}{}^{-} = 70.434\text{ rad}$$

From equation (5), $\Delta\varphi = \varphi_2 - \varphi_1$

$$\Delta\varphi^{+} = 3.620\text{ rad}$$

$$\Delta\varphi^{-} = 3.707\text{ rad}$$

In real world scenario we will have to find the velocity of wind v and we will have the following data from our setup:

L=0.1 m $\quad T_{\text{TOF}}{}^{+} = 0.288\text{ ms} \quad T_{\text{TOF}}{}^{-} = 0.295\text{ ms}$

$\Delta\varphi^{+} = 3.620\text{ rad} \quad \Delta\varphi^{-} = 3.707\text{ rad}$

$f_1 = 38000\text{ hz} \quad f_2 = 40000\text{ hz}$

Solving for v

From equation (14) and (15):

$$\omega_1 = 238761.0417\text{ rad/s}$$

$$\omega_2 = 251327.4123\text{ rad/s}$$

$$\therefore \quad \Delta\omega = 12566.3706\text{ rad/s}$$

Calculating value of phases

For ω_1

$$\varphi_{\omega_1}^{+} = \omega_1 * T_{\text{TOF}}{}^{+} = 72.382\text{ rad}$$

$$\varphi_{\omega_1}^{-} = \omega_1 * T_{\text{TOF}}{}^{-} = 74.141\text{ rad}$$

For ω_2

$$\varphi_{\omega_2}^{+} = \omega_2 * T_{\text{TOF}}{}^{+} = 68.763\text{ rad}$$

$$\varphi_{\omega_2}^{-} = \omega_2 * T_{\text{TOF}}{}^{-} = 70.434\text{ rad}$$

From (2) and (12),

$$T_{\text{TOF}} = \frac{\Delta\varphi}{\Delta\omega} = L/(c \pm v)$$

$$T_{\text{TOF}}{}^{+} = \frac{L}{(c+v)} \Rightarrow 0.28804606 = 0.1/(343 + v)$$

$$\boldsymbol{v = 4.166}\text{ m/s}$$

$$T_{\mathrm{TOF}}{}^{-} = \frac{L}{(c - v)} \Rightarrow 0.295130 = 0.1/(343 - v)$$
$$\boldsymbol{v} = 4.16 \text{ m/s}$$

The above results prove that the value of wind speed will be accurately determined by the system.

IX. Acknowledgement

`I would like to thank my supervisor Mr. Roland G. Clarke for all his support during the whole duration of this project, he motivated me and provided me with guidance and valuable feedback throughout the duration of this project.

X. Conclusion

In this paper I have discussed about developing a dual frequency ultrasonic anemometer which utilises the time of flight technique to precisely measure the slipstream. Furthermore, two pairs of ultrasonic sensors can be combined to measure the wind speed and direction in a 2-dimensional plane which is not possible by most other types of anemometer. Thus, the device measures both the speed as well as the direction of the air which is essential for detecting the slipstream zone. The anemometer uses phase detector to calculate the speed of wind. The acoustics attenuation problem faced by pulse sonic anemometer is not an issue due to the usage of phase detection technique. The calculation for speed of sound which is essential for wind speed calculation can be done by this method, moreover, need of temperature measurement is made redundant by using this over-determined system.

The worked-out example proves that this method is precise. It has a fast response rate making it desirable for our purpose. A simulation has been done on NI Multisim platform, but further test needs to be performed in the real world for the validation of this system.

References

[1] S. Killen, S. Marras, J. Steffensen and D. McKenzie, "Aerobic capacity influences the spatial position of individuals within fish schools", Proceedings of the Royal Society B: Biological Sciences, vol. 279, no. 1727, pp. 357-364, 2011. Available: 10.1098/rspb.2011.1006 [Accessed 2 February 2020].

[2] M. VANDERMOLEN, J. GASH and J. ELBERS, "Sonic anemometer (co)sine response and flux measurementII. The effect of introducing an angle of attack dependent calibration", Agricultural and Forest Meteorology, vol. 122, no. 1-2, pp. 95-109, 2004. Available: 10.1016/s0168-1923(03)00223-5.

[3] F. Durst, M. Zaré and G. Wigley, "Laser-Doppler anemometry and its application to flow investigations related to the environment of vegetation", Boundary-Layer Meteorology, vol. 8, no. 3-4, pp. 281-322, 1975. Available: 10.1007/bf02153554 [Accessed 3 May 2020].

[4] D. Banfield and R. Dissly, "A Martian sonic anemometer", 2005 IEEE Aerospace Conference, 2005. Available: 10.1109/aero.2005.1559354 [Accessed 6 May 2020].

[5] D. Camuffo, Microclimate for cultural heritage. Amsterdam: Elsevier, 1998, pp. 483-511.

[6] J. Kaimal, Proceedings of the Dynamic Flow Conference 1978 on Dynamic Measurements in Unsteady Flows, 1st ed. Springer Science+Business Media B.V, 1979, pp. 551-565.

[7] C. HUANG, K. HUANG, Y. LI and M. YOUNG, "TWO-FREQUENCY CONTINUOUS WAVE ULTRASONIC SYSTEM FOR TEMPERATURE MEASUREMENT IN AN INFANT INCUBATOR", Biomedical Engineering: Applications, Basis and Communications, vol. 13, no. 06, pp. 296-303, 2001. Available: 10.4015/s1016237201000376.

[8] C. Huang, M. Young and Y. Li, "Multiple-frequency continuous wave ultrasonic system for accurate distance measurement", *Review of Scientific Instruments*, vol. 70, no. 2, pp. 1452-1458, 1999. Available: 10.1063/1.1149604.

[9] P. Chandran, R. Bhakthavatchalu and P. Kumar, "Time of flight measurement system for an ultrasonic anemometer", 2016 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT), 2016. Available: 10.1109/iccicct.2016.7988049

[10] V. Yadav, A. Sinha and A. Khosla, "Design and implementation of ultrasonic anemometer", 2017 4th International Conference on Power, Control & Embedded Systems (ICPCES), 2017. Available: 10.1109/icpces.2017.8117645 [Accessed 3 May 2020].