To Measure Wind Speed using the theory of One-dimensional Ultrasonic Anemometer

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Abstract

Ultrasonic anemometer (UA) is a core application in natural environment measurement. As well known, mechanical anemometer works well in good weather but it is not suitable to be applied in bad environment such as polar region and upper air. On the other hand, ultrasonic anemometer works well in most situations. Moreover, ultrasonic anemometer has wider detectable wind speed range. It can be said that ultrasonic anemometer is a more advanced instrument to measure wind velocity. In this paper, the theory of ultrasonic anemometer is first discussed. Using the theory, a test bed is then designed and constructed to measure one-dimensional wind speed. Active Butterworth filter is introduced into the circuit in order to increase the stability and accuracy. Furthermore, we test the one-dimensional ultrasonic anemometer and compare the measured wind speed with theoretical wind speed measured by a thermal anemometer device. Error is also discussed and improvement has also made during the experiment.

Key words: Ultrasonic anemometer; One-dimensional; Wind speed; Butterworth filter
Measure wind speed using the theory of one-dimensional ultrasonic anemometer.
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1 Introduction

1.1 Background

An anemometer is a device to measure the wind speed and direction. Wind measurement is significant for detecting wind in industrial field. Besides, wind measurement can be applied in environment monitoring and controlling systems, air conditioning systems and so on [1].

There are several types of anemometer which are mostly used: mechanical anemometer, sonic anemometer, thermal anemometer and so on.

1.2 Scope

1.2.1 Study focus

The focus of the study is on the sonic anemometer field. There is one type of sonic anemometer called ultrasonic anemometer (UA), which use ultrasonic propagation time as the parameter to wind speed. The ultrasonic is generated from an ultrasonic source and received by an ultrasonic receiver. Due to the speed of sound is really fast, the propagation time is really short. Assume that the distance between the transceivers is around 0.1 m, the theoretical propagation time will be 0.3 ms. When wind speed is parallel to the sound propagation direction, the time will be shorter and vice versa. By measuring the propagation time, the wind speed can be determined.
There are some industrial ultrasonic anemometer productions such as figure 1. 1-A is an example of a two-dimensional ultrasonic anemometer which is widely used in meteorology. It is usually placed in a weather station. It collects wind information including speed, direction and variation trend. There are three transducers at the tops of the sticks. Two-dimension means that it can only measure the wind which is parallel to the plane consisting by the three transducers. 1-B is an example of three-dimensional ultrasonic anemometer. As can be recognized from the figure, the transducer’s number increases to 6. They are three pairs of transducers. Each pair stands on one axis. Three axes allow the anemometer to measure three-dimensional wind. This anemometer uses the sound propagation time as parameter to wind speed. Wind speed can be calculated as a certain distance divide the propagation time.

One way to improve the ultrasonic anemometer is to increase the number of transducers [2]. More transducers will increase the accuracy because it increases the reference axis. It will also increase the sensitivity due to it decreases the measurement interval. It is the same meaning with increasing the sampling rate.

Since sound is a longitude wave, the wave propagation time can be measured by two ways. The first is by measuring the time difference between transmitted pulse and received pulse. This requires the source generate an impulse wave. The other way is by sending continuous
wave. In this way, the propagation time is determined by measuring the phase difference between the transmitted signal and the received signal.

1.2.2 Overall study aim

The physics department at HiG has an interest in measuring wind speed. Therefore the writers simulate a situation and use electronic circuits to measure a physical phenomenon. The idea of this paper is to find the influence from wind speed and temperature to sound propagation. In order to do this, there are some objectives which need to achieve:

1. Construct the test bed which consists of ultrasonic transmitter and receiver. This test bed is able to generate different one-dimensional wind speed.
2. Measure the sound propagation time using digital oscilloscope in different wind velocity.
3. Analyze the data and compare the measured wind speed with the theoretical values.

Fig. 2. The graphic main idea of this thesis

Figure 2 is the main design of the thesis in a graphic way. The dash rectangle box is the test bed where the measurement is done, the arrows are the variables need to be controlled or measured and the dotted line is the propagation distance over which time is measured.

The generator provides power to the ultrasonic source which transmits ultrasound. The sound wave travels through conditional surroundings to the receiver. The propagation time is relevant to wind speed and temperature. Digital oscilloscope is used to measure the time difference between transmit and receive which is the propagation time. Filter is used to eliminate the frequency which is not equal to the transmitted signal.
The reason to choose the ultrasound instead of audio sound is that ultrasonic has much higher frequency than audio sound. Higher frequency sound has less noise in nature. If Audio sound is used, there are noises from the surroundings and instruments such as human voice and fans. In addition, higher frequency signal has shorter wavelength. This increases the resolution of the results.

In order to discuss the influence from wind speed and temperature to sound travel, wind and temperature must be controllable or measurable. A fan will be used to provide stable wind speeds to the bed. Then repeat the experiment under different temperature surroundings.

1.2.3 Included

In this paper, the writers will build a simple module to measure the ultrasonic propagation time affected by the one-dimensional wind speed at different temperatures. In the experiment, the wind speed is a controllable variable and the temperature is an observable variable. The reader should achieve basic knowledge about how ultrasonic anemometer works. Through analyzing the data, the probable sources of error will be discussed.

1.2.4 Not included

Some factors will not be discussed in this study such as humidity. The humidity will affect the sound propagation. However as the experiment is done indoors, the humidity can be regarded as a constant and a normal value. So the humidity will not have too much influence to the sound propagation. In this experiment, the wind speed and the temperature are the two factors that be considered. Other factors are ignored.
2 Theory and Method

In short, the main study objectives are:
1. Construct the test bed.
2. Measure the sound propagation in different wind velocity.
3. Analyze the data.

Obviously, the research strategy is experimental. The authors construct a test bed to measure the effect from wind to sound propagation. The experiment data are collected and compared with the theoretical values. Through analyzing the data, the accuracy and the improvement solutions are discussed.

2.1 Theory

2.1.1 Mechanical anemometers

Mechanical anemometers are most commonly used because they are easy constructed. Among them, there are two typical types of mechanical anemometer device: cup-type and windmill [3-4]. The cup-type anemometer determines the wind speed by counting the cups bed rotation in a certain time. In another word, the cup-type anemometer measures the distance which the wind travels. Then using the distance divided by the travel time, the wind speed can be calculated. The structural difference between cup-type and windmill is the direction of the rotation axis. As we can see from figure 3, the cup-type rotation axis is vertical. On the other hand, windmill rotation axis is parallel to the wind direction and it has an empennage to turn itself towards the wind. The windmill anemometer is mainly used to record the temporary wind direction and continuous variation.
2.1.2 Sonic anemometer

The anemometers described above use the wind kinetic energy to support the measurement. They do not need any extra source to provide parameters. In addition, there are some other types of anemometer which introduce extra sources as parameters to wind speed, for example the speed of sound.

Sound transmits in form of a longitude wave. It propagates by changing the density of the medium. In air, sound propagates by changing the air pressure along its moving direction. The speed of sound is about 340 m/s at temperature 15 °C. When the temperature increases, the speed of sound will increase. The speed of sound in dry air can be calculated as

\[
V_s = 331.3 \frac{m}{s} \cdot \sqrt{\frac{T_K}{273.15 \degree C}} = 331.3 \frac{m}{s} \cdot \sqrt{1 + \frac{T_c}{273.15 \degree C}}
\]

Where \( T_K \) is the temperature in Kelvin, \( T_c \) is the temperature in centigrade degree [5].

By applying Taylor expansion [6], this expression will derive into an easier format. The reason why simplify this equation is that microcontroller is not able to do square calculations. For industrial applications, the data are collected and processed by a microcontroller. So only simplify the equation, a microcontroller is able to be introduced into the industrial productions.

Use the first two terms of Taylor expansion to equation 1

\[
V_s = 331.3 \frac{m}{s} \left(1 + \frac{T_c}{2 \cdot 273.15}\right) = 331.3 + 0.606 T_c (m/s)
\]
The errors between the complicated formula and the simplified formula are calculated using Matlab. The code and the curves are shown in Appendix A. For room temperature, the error between the complicated formula and the simplified formula is about 0.1 m/s. As this value is small and for easy calculation, the simplified formula is treated as the theoretical speed of sound formula.

The flow in medium effects the wave propagation passing though. Wind is free, it occurs anywhere in air. Sound waves transmit in air will have interference when wind blows. If the sound has the same direction to the wind, it will go faster. If the sound has the negative direction to the wind, it will go slower. Since speed of sound can be considered as constant in static air, the wind speed can be determined if the sound propagation speed changes.

This paper uses a non-mechanical way to measure the wind speed. Ultrasound is introduced to do the study. Human ear can hear the sound between 20 Hz to 20 kHz which is called audio frequency. Ultrasound is the sound whose frequency is above 20 kHz.

The advantage of sonic anemometer compares with the other mechanical type of anemometer is that it regards sound as parameter. Sound is a wave, the only thing affects its propagation is the medium. Sonic anemometer will be mostly affected by temperature and pressure. By definition, the mechanical anemometer has a lot of influencing factors such as density, friction and so on. That is to say, sonic anemometer can be applied in variety of environment. In addition, when measuring the wind, sonic anemometer usually measures some factors at the same time using extra sensors, for example, temperature. The temperature values can then be used for calibration of the measurement according to equation 2. Besides, the maximum and minimum wind strength that a sonic anemometer can reach is much wider than the mechanical anemometer [7]. To sum up, the advantages of the sonic anemometers are reflected in versatility, accuracy, measured factor number and the range.

Another advantage of sonic anemometer is that it can measure three-dimensional wind. If the receiver number is equal or larger than 3, it can improve to be a three-dimensional anemometer. For mechanical anemometer, like the cup-type anemometer, it can only measure the wind speed but not the direction. The windmill type anemometer can measure wind speed and two-dimensional direction. Three-dimensional sonic anemometer can measure wind speed and three-dimensional direction.
2.2 Method

There are two ways to determine the wind velocity using sonic anemometer. The measurement method used in this experiment is called time of flight (TOF) [8-9]. From the name it can be known that the time is the key point. The time refers to the propagation time that the ultrasound used to travel from the transmitter to the receiver. The TOF method requires that the transducers have time synchronization. Only if the transducers time is synchronized, the time difference between the transmitted signal and the received signal can be measured. The experiment uses an oscilloscope to observe the time difference between received signal and transmitted signal. These two signals are time synchronized due to that they use the same instrument to measure the phase. In this way, they both related to the reference time inside the oscilloscope. For two-dimensional or three-dimensional anemometer, wind will affect the propagation time. By comparing with the no wind situation, the wind speed on each axis can be known. Use vector plus, the real wind speed and direction can be known.

Another normally used method in ultrasonic anemometer application is angle of arrival (AOA) [1]. Instead of using the time as a parameter, it uses the arrival signal angle as parameter. AOA method can only be applied in two-dimensional or three-dimensional anemometer. In this method, the wind speed is determined by the received signal strength and the direction is determined by the received signal directions. Wind will change the received strength and angle. By comparing the no wind signal strength and no wind received signal angle, the wind velocity can be measured. Figure 4 illustrates the AOA method. T is the transmitter and R is the receiver. The line is the detected angle when there is no wind. The dotted line is the angle when wind blows. The length of the dotted line stands for the received signal strength. The little short line is the detected wind velocity, containing both speed and direction information.
2.3 Setup

2.3.1 Test bed

Constructing the anemometer module requires application of the ultrasonic transmitter, ultrasonic receiver and fan into a conditional surrounding. The factors of this surrounding are controllable or measurable. In this study, the test bed is placed indoor where the experiment is executed.

Figure 5 is the idea of the test bed. The entire measurement is based on this. The ultrasonic transmitter and the receiver are MA40S4R/S, a combined transmitter and receiver, see datasheet in Appendix B. There is also a fan that provided wind to this bed. The fan is
supplied by an AC power source. The wind speed is proportional to the rotational speed of the fan which is proportional to the supply voltage. So the wind speed can be adjusted by varying the supply voltage. Therefore, a voltage controller is used to control the supply voltage of the fan. The controller used in this experiment is a 230 V, 50~60 Hz, 5 steps adjustable AC voltage controller. This voltage controller can be regarded as the wind controller of the fan.

The ultrasonic transmitter needs input signal to run the function. From the datasheet (see Appendix B), the input voltage is 20 Vp-p, 40 kHz continuous rectangular wave. So a function generator is used to generate the allowable input. The output of the generator is set to 20 Vp-p, 40 kHz, 0 offset, 50% duty cycle. To verify that the transmitter transmits a 40 kHz ultrasound, a Pettersson ultrasound detector D 230 is used. The Pettersson ultrasound detector basically is a device with a mixer and an adjustable local oscillator. It mixes the received ultrasonic with the local oscillator signal hereby transforms the ultrasound to audio frequency that humans can hear. The local oscillator has been adjusted to around 39.9 kHz which is near the input frequency, 40 kHz, of the transmitter. The output audio will have the frequency 100 Hz, which is in the audio frequency range. If the transmitter works properly, there will be audible sound coming out.

After testing the transmitter, the receiver needs to be tested. The way to test it is to find out if it can receive the ultrasound that the transmitter sends. Start with placing the transducers on a project board. The minimum allowed detectable range of the components uses in experiment is 200 mm. Through testing, distance a little less than this number is still detectable and usable. The longest distance in the project board tests in the experiment is 200 mm placing the transducers across corners of the board. Connect the transmitter to the generator and connect the receiver to the oscilloscope. Verify that the frequency of the received signal is about 40 kHz. If so the receiver can receive ultrasonic. In order to check if the received signal is the ultrasonic signal that the transmitter sends, the received signal needs to be confirmed. As it is a sound wave, the speed of it must be around 340 m/s.

Directly measure the speed of the sound is difficult. Instead of measuring the speed, measuring the distance change in a certain time period is easier and more feasible. The time difference is measured by the digital oscilloscope. The oscilloscope can determine the time difference between two cursors. The cursors are adjusted to the moment when the square wave starts to go high and the sine wave reaches the bottom. The moment is determined by
observation. The reason why the time difference is between the rising edge of the square wave and the minima of the sine wave is that when square goes high it started to compress the air. Then the air density started to increase and positive slope appeared in sine wave.

\[ \Delta \text{stands for time difference or distance difference. } T \text{ is the transmitter and } R \text{ is the receiver.} \]

Figure 6 is the way to determine the speed of the received signal. First the transmitter and the receiver have been placed in a certain distance. Then change the distance a little bit. The changed distance has limitation. If the time difference is too large that moves a few periods, it becomes unable to know the exact time difference. Using the formula

\[ \lambda = \frac{V_S}{f} \]

With \( V_S = 340 \text{ m/s} \) and \( f = 40 \text{ kHz} \) gives the wavelength, which is around 8.5 mm. So when changing the receiver’s position, it can not move further than 8.5 mm, otherwise it goes outside a certain cycle. Measure the distance between the transmitter and the receiver and travel time each time. Calculated the time difference and distance difference and used the formula

\[ V_S = \frac{\Delta d}{\Delta t} \]

the signal speed can be calculated.

The signal used in this experiment is continuous square wave. The propagation time is the key information that needs to observe. In this experiment, a digital oscilloscope is used to determine the time difference between transmitting and receiving. The input signal of the transmitter is connected to the oscilloscope channel one and the output signal of the receiver
is connected to channel two. By reading the time difference of the two signals, the propagation time can be determined.

After connecting the circuit, the received signal is weak and filled with noise. Also, the signal is unstable and keeps bouncing. So the run/stop function on the oscilloscope is used to observe the signal shape at a certain time. The minima of the received signal need to be found by visual which makes it have errors. Instead of reading the minima once, the writers read the minima 10 times. Removed the maximum and the minimum values, and then found the average of the rest numbers. This move can decrease the errors from observation.

The transmitter has been plugged in the project board. Next plug the receiver in and keep the distance between the transmitter and receiver is about 200 mm. The decrease distance is kept in range of 8.5 mm. That is to say, the minimum distance between the transmitter and the receiver in the experiment is larger than 191.5 mm. Assumed that the speed of sound is 340 m/s, with equation 5

\[ t = \frac{S}{V} \quad (5) \]

It spends 588.2 μs to travel the minimum allowable distance between the transmitter and the receiver. The ultrasonic frequency is 40 kHz, using the formula

\[ T = \frac{1}{f} \quad (6) \]

so the period is 25μs. This means that when the ultrasound reaches the receiver, the received signal is several periods behind the transmitted signal. Decrease the distance a little twice and measure the distance and time difference. The measured data is shown in table 1. Also, in order to compare with the theoretical value, the surrounding temperature is measured which is 20.6 °C
Tab. 1. The data measured in the experiment to determine the speed of the signal according to figure 6. Time resolution=0.2 μs

<table>
<thead>
<tr>
<th>Group number</th>
<th>Distance (mm)</th>
<th>Time difference (μs)</th>
<th>Average Time (μs)</th>
<th>Signal speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>d1=199.7</td>
<td>31</td>
<td>29.2</td>
<td>27.6</td>
</tr>
<tr>
<td></td>
<td>△d12=3.9</td>
<td>28.2</td>
<td>29.4</td>
<td>29.4</td>
</tr>
<tr>
<td>2</td>
<td>d2=195.8</td>
<td>17.8</td>
<td>17.6</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>△d23=3.5</td>
<td>17</td>
<td>19.4</td>
<td>19.6</td>
</tr>
<tr>
<td>3</td>
<td>d3=192.3</td>
<td>8.4</td>
<td>7.6</td>
<td>9.4</td>
</tr>
</tbody>
</table>
|              | △d34=6.8    | 7.2                  | 9.4               | 9.4               |                  | 10

As shown in table 1, the underline time differences are the maximum and minimum values. As the noise has great effect to the received signal, the time difference is bouncing in a large range. This will bring large errors to the results. So the average time is calculated using the other eight data. By doing this, the biggest errors are eliminated. The speed is calculated using the formula 4.

The average speed of the received signal calculated from the table and the formula is 344.1 m/s. Check the datasheet of the speed of sound, \( V_s = 343.4 m/s \) at 20 °C. The received signal speed is almost equal to the theoretical value of the speed of sound. So it is the ultrasound signal sends from the transmitter.

Since the signal strength is weak, ways to improve the measurement reliability need to be found. One way is to add reflector. This can increase the signal strength prominently. However, if the signal reflects, it is impossible to know the exact length which the signal travels. Another way is to construct the transmitter and the receiver so that the two components somehow can face each other. Also, the wind can pass through the transmitter and the receiver freely. In order to achieve this, a holder is designed and built.

The holder is made by wooden pieces. It is two thin wooden sticks fixes on a big piece of wooden base. The transducers are plugged in the stick about 6 cm high from the base and face to each other. The sticks are thin so that they will not cause too much influence to wind. The height is chosen for the purpose that it neither can be too close to the base nor too high along
the stick. If it is too low, when the wind blows, wind turbulence may appear which has effect on the wind speed and direction. If it is too high, strong wind will bend the thin stick, which brings distance errors. The distance between the transducers has to be exactly measured. The preciseness needed to be less than 1 mm, so the time difference error can be controlled in an acceptable range. Micrometer has the resolution of 0.1 mm. The minimum detectable range is chosen to be the distance between the transducers. However, 200 mm is too long to use a micrometer to measure directly. So another advanced way is necessary to accurately measure the distance between the transducers. The received signal is several cycles behind the transmitted signal. If the cycle number, \( n \), is known then the distance can be calculated by

\[
L = (n \cdot T + \Delta \phi) \cdot V_s
\]

where \( L \) is the distance, \( T \) is the period, \( \Delta \phi \) is the time difference on the oscilloscope and \( V_s \) is the sound speed.

Theoretically, period should be exactly equal to 25 \( \mu \)s. However, the oscilloscope used in this study is not so stable. It will not produce a perfect 40 kHz square wave. It decreases a few hundreds Hz automatically. So the frequency used in this experiment is actually 39.7 kHz, whose period turns to be 25.2 \( \mu \)s. The temperature is measured 19.9 °C. Using the speed of sound formula, the speed is calculated to be 343 m/s. \( \Delta \phi \) is read from the oscilloscope whose channels are connected to the transmitted signal and received signal. The transmitted signal is a square wave and the received signal is a sine wave, the phase shift is the time between the rising edge of the square wave and the minima of the sine wave. \( \Delta \phi \) is measured to be 10.0 \( \mu \)s.

\( L \) can firstly be measured by ruler; the accuracy can reach 1 mm and estimation can reach 0.1 mm. The distance is measured \( L_1 = 21.42 \) cm. Rearranging equation 7 gives equation 8

\[
n = \frac{L}{V_s} - \frac{\Delta \phi}{T}
\]

Using equation 8, \( n_1 \approx 24.38 \). \( n \) can only be integer. So \( n \) is determined to be 24 and calculated the real distance using equation 7, \( L = 210.9 \) mm. The resolution reaches 0.1 mm in this value which means the calculated distance 210.9 mm is accurate number, no estimate part, which is 10 times better than using the ruler. As the transducers are plugged into the thin sticks instead of fixed into the sticks, there will be tiny movement on the distance between the transducers. The maximum movement is less than 1 mm. In order to increase the accuracy,
the actual distance between the transducers has to be re-calculated each time before measurement. Once the transducers are placed onto the bed, the received signal is clearly sin-shaped with little ripples.

2.3.2 Measurement system

The measurement system is used to collect the information from the test bed. Digital oscilloscope is the most important one belongs to it. Some other equipment, such as thermometer and thermal anemometer, are also used.

Digital oscilloscope is applied to measure the time difference between the transmitted signal and received signal. Like what has been done in the previous section, using equation 4, the signal speeds in different wind speed can be calculated. Since the received signal is filled with some high frequency noise, a component which can eliminate the noise is necessary.

A filter is designed to eliminate the high frequency noise. A low pass filter whose cutoff frequency is around 50 kHz will be a suitable filter. Active filter will be a good choice. The cutoff frequency can be easily adjusted by varying the resistance or the capacitance. Butterworth type filter is selected due to it has smooth amplitude response. In this experiment, the noise has very high frequency. Even though the Butterworth filter has small slope, the very high frequency noise will be eliminate anyway. Another advantage of Butterworth filter is that it has no ripples in amplitude response. So no certain frequency spectrum will have unnormal different gain from the others. The filter order is chosen to be 2. A 2nd order filter has theoretical slope of 40 dB/dec [10]. This value is good enough for this experiment. A typical sallen-key lowpass filter circuit [11] is shown in figure 7.

![Fig. 7. Lowpass sallen-key filter](image-url)
The cutoff frequency and Q value are calculated as

$$f_c = \frac{1}{2\pi \sqrt{R_1 R_2 C_1 C_2}}$$  \hspace{1cm} (9)$$

$$Q = \sqrt{\frac{R_1 R_2 C_1 C_2}{C_2(R_1 + R_2)}}$$  \hspace{1cm} (10)$$

A Butterworth filter is one type of sallen-key whose Q value is equal to $1/\sqrt{2} = 0.7071$ [12].

In order to make Q value equal to 0.7071, equation 10 should be equal to $1/\sqrt{2}$.

Assume that $R_2 = mR_1 = mR$, $C_2 = nC_1 = nC$. Then equation 10 becomes

$$\frac{RC\sqrt{mn}}{CRn(1 + m)} = \frac{\sqrt{mn}}{n(1 + m)} = \frac{1}{\sqrt{2}}$$  \hspace{1cm} (11)$$

Take square of each side of equation 11

$$\left(\frac{\sqrt{mn}}{n(1 + m)}\right)^2 = \frac{m}{n(1 + m^2 + 2m)} = \frac{1}{2}$$  \hspace{1cm} (12)$$

Choose $m=1$ $n=0.5$

Then $R_2 = R_1$, $C_2 = 0.5C_1$

Calculate the cutoff frequency using equation 9

$$f_c = \frac{1}{2\pi RC \sqrt{0.5}}$$  \hspace{1cm} (13)$$

Design the cutoff frequency to 50 kHz, with the equation 13

$$RC = 4.5016 \cdot 10^{-6}$$

Choose a good value for resistors, $R=680 \, \Omega$. Calculate $C_2 = 0.5C_1 = 3.31 \, nF$. Pick a close value for capacitors $C_2 = 3.3 \, nF$, $C_1 = 6.6 \, nF$.

The designed lowpass Butterworth circuit is like figure 8 below.
Fig. 8. 2\textsuperscript{nd} order lowpass Butterworth filter design. Amplifier power is not displayed

The resistances values are 680 Ω, the capacitance are 6.6 nF and 3.3 nF and the amplifier is LM741. The cutoff frequency and Q value, using formula 9 and 10, are calculated to be $f_c \approx 50.15kHz$ and $Q = 1/\sqrt{2}$.

The transfer function of the sallen-key lowpass filter is [13]

$$H(s) = \frac{1}{1 + C_1(R_1 + R_2)s + R_1R_2C_1C_2s^2}$$  \hspace{1cm} (14)

When inserting the values above into equation 14, the following transfer function can achieve.

$$H(s) = \frac{1}{1 + 4.488 \cdot 10^{-6}s + 1.0071072 \cdot 10^{-11}s^2}$$  \hspace{1cm} (15)

Use matlab to plot this transfer function in equation 15 and change the axis to suitable range. Result is shown in figure 9
As the data tip shows in the figure, the unit of the cutoff frequency is rad/s. Then change the cutoff frequency into Hz, using the formula

\[ f_c = \frac{\omega_c}{2\pi} \]  

The cutoff frequency is calculated to be 50.16 kHz. Therefore, this filter performs as designed.

There will be one problem if the filter is introduced into the circuit. When signal goes through a filter, it will not finish the progress immediately. Instead, it takes some time to go through each component. Therefore, there will be a time delay between the input and output of the filter.

Figure 10 is the time delay for different order of lowpass Butterworth filter. N stands for filter order. The normalized frequency is calculated using the actual signal frequency divided by the cutoff frequency \( f / f_c \). The normalized delay is calculated using actual delay multiplied by the cutoff frequency \( d \cdot f_c \) [14].
The filter used in the experiment is a 2\textsuperscript{nd} order lowpass Butterworth filter, whose cutoff frequency is 50 kHz. The actual frequency is the input frequency to the transmitter, which is 39.7 kHz. The normalized frequency in this case is 0.8. Corresponding to figure, 2\textsuperscript{nd} order, normalized frequency is 0.8, the normalized delay is 0.25. So the time delay can be calculated \[ d = 5 \mu s \]. The signal will spend 5 \mu s to pass though the filter. The time delay will affect the phase shift on the oscilloscope. It will cause the phase shift to be 5 \mu s more than the actual time delay. When calculating the actual length between the transducers, the filter caused time delay has to be eliminated. Nevertheless, when calculating the propagation time difference, the time delay will not cause any difference, because the time delays canceled each other.

Use Multisim to simulation the filter delay. Use the function generator to generate a sine wave whose frequency is 39.7 kHz. Use an oscilloscope to find out the actual delay of the filter. The result is shown in figure 11.
As can be seen in the figure, the actual delay of the filter is 5.3 μs. The results are similar to the literature data and more precise. 5.3 μs delay is used for further calculation.

This experiment is designed to find out the effect from wind speed to sound. Fan is used to generate different speed wind. If the ratio between sound propagation and wind speed is the objective, a theoretical anemometer is needed. This anemometer is used to measure the wind theoretically, so that the theoretical values can be used as parameters when doing the data analysis. In this experiment, the scientific thermal anemometer’s resolution is 0.01 m/s. Since the sound speed is around 340 m/s, less than 0.01 m/s wind speed errors will not cause too much time errors. So this anemometer is good enough. The anemometer will be set near the transmitter and the receiver so that it is able to measure the wind speed along the propagation path.

Another factor which will affect the sound speed is temperature. Thermometer is the device to measure the temperature. It is an electronics thermometer and its precision can reach 0.1 °C. From the speed of sound formula, 0.1 °C error will cause 0.06 m/s sound speed error. Compare with 340 m/s, this is negligible. In this experiment, two thermometers are used to
determine the temperature. One is in the thermal anemometer and the other one is an independent thermometer. The final temperature is the average of them.

2.3.3 Framework for data analysis

The wind is a form of medium movement. As the sound travels by changing the medium’s density, the effect from the wind velocity can regard as vector. The sound travels in wind can be calculated as vector plus, both speed and direction are the considerations. For one-dimensional wind, the sound speed can direct plus the wind speed and regard as the signal speed.

As mentioned above, the speed of sound can be calculated as equation 2. In different temperature, speed of sound has different speed. So the propagation time will be different. As the experiment focused on one-dimensional wind, the wind speed can be either positive (the direction of the wind is the same as the signal) or negative (the direction of the wind is the opposite of the signal). For the distance 200 mm, which is the minimum detectable length between the transducers used in this experiment, the propagation time is varied due to temperature and wind speed. The propagation time is calculated as

\[ t_w = \frac{L}{V_o + V_w} \]  

(17)

Where L is the length between the transducers
V₀ is the speed of sound without wind
V₇ is the speed of sound when wind blows

In this experiment, the maximum wind speed is about 10 m/s, which is 36 km/h. For daily urban life, this strength of wind is not commonly seen. The wind comes from both positive side and negative side. Positive side means the wind direction is the same as the sound propagation direction. Negative side means that the wind direction is the against the propagation direction. Assume that the sound speed is 340 m/s and the distance between the transmitter and the receiver is 200 mm, the wind speed will cause a time difference using equations 17 and 18

\[ t_0 = \frac{L}{V_0} \]  

(18)
\[
\Delta t = t_w - t_0 = \frac{-L \cdot V_w}{V_0^2 + V_0 V_w}
\]  \hspace{1cm} (19)

\(\Delta t\) is the time difference between different wind speed
\(t_w\) is the phase shift when wind blows
\(t_0\) is the phase shift when no wind

The maximum time differences, as shown in equation 19, are calculated to be 16.8 \(\mu\)s or 17.8 \(\mu\)s. As the period of ultrasonic is 25 \(\mu\)s, for as strong as 10 m/s wind, the changes of the propagation time are still in the same cycle. So the change of propagation time is easy to find on the oscilloscope.

Plot the propagation time in different wind speed and temperature into figure 12. The data used to plot this figure can be found in Appendix C.

![](image)

*Fig. 12. The propagation time due to different wind speed and temperature*

The figure 12 shows the theoretical propagation time to travel a 200 mm distance. In the experiment, the distance between the transducers is about this distance but not exactly equal to. This is the basic theory for later wind speed measurement.
The measured data in this experiment is time difference between no wind situation and different wind speed situation. First measuring the propagation time with no wind, then measure the propagation time when wind blowing. Using the propagation time difference and the length information, a calculated wind speed can be achieved. This wind speed is measured from the test bed. Next, compare the measured wind speed with the theoretical value which is measured from the thermal anemometer. The reason why the errors appeared can be discussed.

2.4 **Limitation**

The limitation of this experiment is mainly about the environment. As the equipment is very sensitive, the experiment is better to be hold in ideal surroundings. Wind turbulence has great effect to the final results [15]. Therefore, the wind path has to be a clear way. Any obstacles have to avoid. In order to avoid all the possible wind turbulence effect, a tunnel has introduced to the experiment. The tunnel is paper made, about 0.25 m in diameter, 1.5 m in length and cylinder shape. Three holes are drilled so that the transducers and the thermal anemometer can be stretched into the tunnel. The tunnel can make sure the wind is in one-dimensional, stable, and homogenous. Also, the tunnel can help to avoid outside interference such as environment wind and external ultrasound. With the tunnel, the experiment can be regarded as it is proceeding in ideal surrounding.

Furthermore, the final parameter that got from the experiment is the propagation time. The focus of this experiment is about to find out the wind speed. If the wind speed can be automatic calculated, it will be much better. The limitation of this experiment is that the data need to be calculated by hand so that the wind speed can be found. The focus of this thesis is at the measurement part instead of signal processing part. In addition, as mentioned above, the received signal is not so sine shaped. It can not use the auto-measure function to find out the phase shift by the oscilloscope. So the final parameter that can get from the devices has the phase shift. The wind has to be calculated from this value.
2.5 Preparation

Function generator is set to 40 kHz, 20 Vpp, 0 offset, 50% duty cycle square wave. The output of the generator is connected to a T connecter, which divided the output signal of the generator into two same signals. One of them is connected to one port of the transmitter and the other one is connected to oscilloscope channel 1. The other port of the transmitter is connected to ground. The signal will send from the transmitter and received by the receiver. One port of the receiver is connected to the input of the 2\textsuperscript{nd} order lowpass Butterworth filter and the other port is connected to the ground. The output of the filter is connected to the oscilloscope channel 2. A DC power supply is used to offer +/- 15V to the amplifier. All the ground wires are connected together.

Measure the temperatures using the thermometer. Place the equipment at a suitable location so that the fan, the transmitter and the receiver are in a line. Firstly, measure the propagation time without wind. Then, control the wind speed use the voltage controller. Measure the wind speed at the middle of the connection line of the transducers. Remove the thermal anemometer and measure the propagation time. Next, change the wind speed level and repeat the steps. Finally, measure the temperatures again. The temperatures are measured 2 times at the beginning of the measurement and 2 times after the experiment. Record the average temperature calculated from the 4 data.
3 Results

3.1 Experiment

The maximum wind speed that the fan can supply in this experiment is about 10 m/s, which is 36 km/h. The temperature is room temperature, which is around 20 °C.

Though testing, the received signal is not perfectly stable. It is blinking. When read the phase shift, the signal needs to be stopped by pressing the run/stop button. The phase shift will not be the same value each time. So measure the phase shift 10 times and calculate the average time. The theoretical wind speed is measured using the thermal anemometer. The reading on the thermal anemometer is changing all the time. Record the wind speed on the thermal anemometer every 5 seconds and repeat the reading 5 times.

This experiment is divided into two similar parts. The first part is the positive wind and the second part is the negative wind.

3.2 Results

3.2.1 Positive wind

Start with the positive wind. The transmitter is between the fan and the receiver. Positive wind will increase the speed of sound. For a certain distance, the propagation time will decrease. As mentioned earlier, wind speed less than 10 m/s will not cause a phase shift larger than 1 cycle. Therefore, the phase shift difference which directly read from the oscilloscope is able to be regard as the time difference. Fill the measured data into table 2.
Measure wind speed using the theory of one-dimensional ultrasonic anemometer

As can be seen in the table, there are negative phase shifts. This is because the phase shift is known in the same cycle, for easy calculation, the phase shift is recorded as a negative number instead of the phase shift shown on the oscilloscope. The real shift shown on the oscilloscope can be calculated as period plus the negative number. This means, instead of recording the phase shift on the oscilloscope, the recorded data is calculated by using the phase shift on the oscilloscope minus a period time. By doing this, the number in the table is easy to calculate and more easy to understand.

Calculate the time difference which the signal spends to travel from the transmitter to the receiver when changing the wind speed. The wind speed equation is derived from equation (19)

\[ V_w = \frac{-\Delta t \cdot V^2}{\Delta t \cdot V^0 + L} \]  

(20)

As mentioned in section 2.1, the distance between the transducers has to be re-calculated in order to keep a high accuracy. The average phase shift without wind shown on the oscilloscope is calculated as -4.64 μs. This number has to minus a filter delay time, 5.3 μs, if it is going to be used to calculate the propagation distance. So the actual phase shift value that can be used to calculate distance is -9.97 μs. Add a period to this number,

\[ -9.97 + 25.2 = 15.23 \mu s \] .

This means, the actual length in this experiment, using equation (7), is calculated to be

\[ L = 212.8 \text{mm} \]
Calculate the average theoretical wind speed and measured wind speed and record the data in table 3.

Tab. 3. The calculated positive wind speed

<table>
<thead>
<tr>
<th>Wind level</th>
<th>Theoretical wind speed (m/s)</th>
<th>Average phase shift (μs)</th>
<th>Time difference (μs)</th>
<th>Calculated wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>7.96</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>+3.124</td>
<td>2.71</td>
<td>-5.25</td>
<td>+2.939</td>
</tr>
<tr>
<td>2</td>
<td>+4.102</td>
<td>1.17</td>
<td>-6.79</td>
<td>+3.811</td>
</tr>
<tr>
<td>3</td>
<td>+5.234</td>
<td>-0.70</td>
<td>-8.66</td>
<td>+4.875</td>
</tr>
<tr>
<td>4</td>
<td>+5.992</td>
<td>-1.94</td>
<td>-9.90</td>
<td>+5.585</td>
</tr>
<tr>
<td>5</td>
<td>+7.472</td>
<td>-4.17</td>
<td>-12.13</td>
<td>+6.868</td>
</tr>
</tbody>
</table>

Plot the theoretical value and the calculated value in figure 13.

Fig. 13. The theoretical wind speed and measured wind speed (positive)

Calculate the value of the errors between the theoretical wind speed and measured speed. The errors mentioned in this paper are referred to the difference or the deviation between the
theoretical wind speed measured by the thermal anemometer and the measured speed from the experiment. Also, calculate the error percentage to the theoretical value. Fill the data in table 4.

**Tab. 4. The error of the positive wind situation**

<table>
<thead>
<tr>
<th>Wind level</th>
<th>Theoretical wind speed (m/s)</th>
<th>Calculated wind speed (m/s)</th>
<th>Error value (m/s)</th>
<th>Error percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>+3.124</td>
<td>+2.939</td>
<td>-0.185</td>
<td>5.9</td>
</tr>
<tr>
<td>2</td>
<td>+4.102</td>
<td>+3.811</td>
<td>-0.291</td>
<td>7.1</td>
</tr>
<tr>
<td>3</td>
<td>+5.234</td>
<td>+4.875</td>
<td>-0.359</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>+5.992</td>
<td>+5.585</td>
<td>-0.407</td>
<td>6.8</td>
</tr>
<tr>
<td>5</td>
<td>+7.472</td>
<td>+6.868</td>
<td>-0.604</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Plot the error values and error percentage into figure 14 and figure 15.

**Fig. 14. The error value against the theoretical positive wind speed**
Zhou Yufeng; Wang Yan

Measure wind speed using the theory of one-dimensional ultrasonic anemometer

Fig. 15. The error percentage verse the theoretical positive wind speed

3.2.2 Negative wind

Turn the bed so that the fan, the receiver and the transmitter are in a line and the receiver is between the fan and the transmitter. Negative wind will cause the wind speed decrease. The propagation time will increase. Repeat the steps with negative wind. Record the measured data in table 5.

Tab. 5. The measured data (negative wind)

<table>
<thead>
<tr>
<th>Wind level</th>
<th>Wind speed (m/s)</th>
<th>Phase shift (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-4.9</td>
<td>-5.5</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-2.86</td>
<td>-2.88</td>
</tr>
<tr>
<td>2</td>
<td>-3.80</td>
<td>-4.01</td>
</tr>
<tr>
<td>3</td>
<td>-5.02</td>
<td>-5.12</td>
</tr>
<tr>
<td>4</td>
<td>-6.06</td>
<td>-6.04</td>
</tr>
<tr>
<td>5</td>
<td>-8.29</td>
<td>-8.19</td>
</tr>
</tbody>
</table>

Re-calculate the length between the transducers. The average phase shift without wind shown on the oscilloscope is -5.34 μs. Minus a filter delay time 5.3 μs equals to -10.68 μs. Add a period, \( -10.68 + 25.2 = 14.52 \mu s \)

The actual length in this experiment, using the equation 7, is calculated to be
$L = 212.6\, \text{mm}$

Calculate the time difference which the signal spends to travel from the transmitter to the receiver when changing the wind speed. Calculate the wind speed using the equation 20 and record the data in table 6.

### Tab. 6. The calculated negative wind speed

<table>
<thead>
<tr>
<th>Wind level</th>
<th>Theoretical wind speed (m/s)</th>
<th>Average phase shift (µs)</th>
<th>Time difference (µs)</th>
<th>Calculated wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>-5.34</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-2.744</td>
<td>-0.40</td>
<td>4.94</td>
<td>-2.715</td>
</tr>
<tr>
<td>2</td>
<td>-3.816</td>
<td>1.21</td>
<td>6.55</td>
<td>-3.591</td>
</tr>
<tr>
<td>3</td>
<td>-4.994</td>
<td>3.18</td>
<td>8.52</td>
<td>-4.656</td>
</tr>
<tr>
<td>4</td>
<td>-6.004</td>
<td>4.83</td>
<td>10.17</td>
<td>-5.543</td>
</tr>
<tr>
<td>5</td>
<td>-8.148</td>
<td>8.58</td>
<td>13.92</td>
<td>-7.543</td>
</tr>
</tbody>
</table>

Plot the theoretical value and the calculated value in figure 16.
Calculate the value of the errors between the theoretical wind speed and measured speed. Also, calculate the error percentage to the theoretical value. Fill the data in table 7.

Tab. 7. The error of the negative wind situation

<table>
<thead>
<tr>
<th>Wind level</th>
<th>Theoretical wind speed (m/s)</th>
<th>Calculated wind speed (m/s)</th>
<th>Error value (m/s)</th>
<th>Error percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-2.744</td>
<td>-2.715</td>
<td>+0.029</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>-3.816</td>
<td>-3.591</td>
<td>+0.225</td>
<td>5.9</td>
</tr>
<tr>
<td>3</td>
<td>-4.994</td>
<td>-4.656</td>
<td>+0.418</td>
<td>6.8</td>
</tr>
<tr>
<td>4</td>
<td>-6.004</td>
<td>-5.543</td>
<td>+0.461</td>
<td>7.7</td>
</tr>
<tr>
<td>5</td>
<td>-8.148</td>
<td>-7.543</td>
<td>+0.605</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Plot the error values and error percentage into figure 17 and figure 18.

Fig. 17. The error value against the theoretical negative wind speed
3.2.3 Comparison

Combine the absolute error values and the relative error values for positive wind and negative wind into two diagrams. The absolute values of negative wind and the absolute values of the errors are calculated and used in these figures.

![Figure 18: The error percentage verse the theoretical negative wind speed](image)

![Figure 19: The absolute error for positive wind and negative wind](image)
Measure wind speed using the theory of one-dimensional ultrasonic anemometer

Fig. 20. The relative error percentage for positive wind and negative wind
4 Discussion

In the experiment, phase shift between the transmitted signal and the received signal is measured by the oscilloscope. Propagation time is determined by adding cycles to the phase shift. Time difference is the difference between the propagation times in different wind. Wind speed is calculated using the distance divide the time difference.

4.1 Method

4.1.1 Sampling method

The sampling strategy of this experiment is different from the one when testing the signal. For these two experiments, 10 phase shifts are sampled. However, the first testing experiment removed the maxima and the minima, calculated the average with the left 8 samples. The formal experiment, in a different way, used all 10 samples. The reason why different sampling strategies have applied to different experiment is due to the noise strength and the unstable rate. The testing experiment has been done without the lowpass filter and the two transducers are not face to face. The received signal is blinking rapidly and the signal strength is weak. High frequency noise affected a lot on the signal shape under this situation. The signal is blinking rapidly and hard to recognize where the minima is in the testing experiment. By doing this, the accuracy increases but the reliability decreases. On the other hand, when the transducers are placed face to face and after the Butterworth lowpass filter, the signal is much stronger and more stable. The received signal now is much nicer sine-shaped and easy to find out the minima. There is a ripple band at the received signal every time when the transmitted signal changed. The ripple bandwidth is about 1μs and the amplitude is about 100 mV_{pp} which is about 20 % of the amplitude of the received signal. When the signal passed the filter, the ripple is smaller. There are only few ripples instead of a ripple band and the amplitude is about 20 mV_{pp}.

4.1.2 Transducer’s number

There is a way to improve the experiment which is to add one more receiver. Place the transmitter and the two receivers in a line. Make sure that the two receivers are separated less
than a wavelength distance. The advantage of this method is that the two receivers are placed in a short distance so that the phase shifts between the receivers are less than a period. By using a micrometer, the distance between the receivers can be measured precisely. Or still calibrate the distance with no wind. By measuring the phase shift between these two receivers, the wind speed can be calculated. When the calculated wind speeds, the results are accurate. The advantage of this method is that the time difference is short and the result has high resolution. However, the disadvantage of this method decreases the accuracy. It is because the received signals are not stable, they blink a little. So each time when measuring the phase shift, press the run/stop button and record the data. The final phase shift is the average of 10 samples. The transmitted signal is not blinking, only the received signal is changing. The one receiver method has one estimate phase, but the method using two receivers has two estimate phases. For the worst situation, the errors will add or doubled.

4.2 Errors

As can be seen from figure 13 and 16, the measured wind speed follows the pattern of the theoretical wind speed. The measured wind speed is a little less than the theoretical value. The errors are control in a limited range. From figure 19, the limited error range is less than 0.7 m/s for the wind less than 8 m/s. From figure 20, the error percentages are kept less than 9 %. The measured data looks reasonable because the errors are small and the error percentages are in the same level.

There are several ways that may cause the errors. They can be divided into three parts: instrument, observation and environment.

There are two instruments or devices that can cause errors: function generator and filter. The function generator used in this experiment is not an ideal generator. The output of an ideal generator is stable and unchanged. However, the output of the generator used in the experiment is changing. The frequency of the output square wave is changing in a range of 200 Hz. For non-ideal input signal, the transmitter will not generate the designed output signal, In addition, for the same frequency signal, the filter delay is constant. But if the signal frequency is changing, the delay is also changing. Even though each time when changing the wind level, the frequency has been re-adjusted, there still will have some small errors in the
results. The errors brought by the filter are mainly from the delay. As can be seen from the filter simulation figure, the delay is not exactly equal to 5.3 $\mu$s. Even though the delay will cancel each other when calculating the time difference, it will affect the distance calculation. The delay error is less than 0.1 $\mu$s. 0.05 $\mu$s error will cause about 0.2 mm error in propagation length. Compare with the actual length about 210 mm, it is less than 1 ‰ and negligible.

The observation errors are from the oscilloscope and the thermal anemometer. The readings on them are changing all the time. Each time the oscilloscope has been read 10 times and the thermal anemometer has been read 5 times then calculate the average. There are errors when reading the oscilloscope each time. Read the oscilloscope 10 times is only to decrease the error but not cancel it. From table 2 and table 5, the readings on the oscilloscope are spread in ranges. There may be errors when finding the minima of the sine wave. The thermal anemometer reading is also keep changing. So there are also errors when measuring the theoretical wind speed.

Compare with the errors mentioned above, the environment errors have the most effect. The tunnel has eliminated most of the environment factors. There are two environment factors that will cause errors: wind turbulence and dust. Even though there are no obstacles on the wind path, the turbulence will be caused by the holes on the tunnel and the rough surface of the paper tunnel. Wind turbulence has the greatest influence to the wind speed. Turbulence will add vector speed to the original wind. There are also dust in the air, it has small effect to the ultrasonic anemometer but has little effect to the thermal anemometer.

There is one point seems different from the others in figure 20, which is the first error percentage of the negative wind. This point is much smaller than the rest of the points. There are two possible reasons that may cause this problem. The measurement mistake is the first possible reason. This mistake maybe appears at placing the probe of the thermal anemometer. The probe maybe is placed too close to the tunnel wall. Due to the friction, the wind is smaller than in the middle. So the measured theoretical wind is smaller. According to table 7, the theoretical wind is larger than the calculated wind. If the theoretical wind becomes smaller, the difference between them will decrease. This makes the error smaller than the others. The other possible reason is from the wind turbulence. As the wind is small, the environment probably will cause less wind turbulence than usual. Less turbulence will cause less error. This may also be a possibility.
4.3 Strength and weakness

The advantage of ultrasonic anemometer designed in the experiment is that it has high resolution. If the transmitter and the receivers are fixed, the distance between them is a constant. When measure the distance, the accuracy is high, 1 mm at least. The time is measured by oscilloscope whose resolution can easily reach 1 μs. When using the distance divide by the time, the resolution will reach mm/s which is 0.001 m/s. Normally the mechanical anemometer can only reach dm/s which is 0.1 m/s.

The weakness of this experiment is the error brought from the estimation. The received signal is not so stable that there are errors when calculating the speed. The error is unavoidable. Even though the resolution of this device is high, due to eliminate errors and also the environment factors which are not considered, the acquired data has a large part that can not be trusted.

Another weakness of this experiment is that the phase shift shown on the oscilloscope can not automatic measured by the oscilloscope function. It has to be read by observation due to the ripples. The transmitted signal is a square wave, but the received signal is a sine wave. The time difference is between the rising edge of the square wave and the minima of the sine wave. If the readings can be read automatically by machines, the data can be processed by a microcontroller and directly calculated into wind speed.
5 Conclusions

This study produced a basic one-dimensional ultrasonic anemometer using the theory of TOF. The phase shift can be read for the instrument. Apply the readings into equations, the wind speed can be calculated manually. The transducers used in this experiment are cheap and simple functional. The calculated wind speed can limit the error less than 10 % and 1 m/s for the wind less than 10 m/s.

5.1 Improvement

The experiment has been improved a lot since it started. Changes have been made on structures, equipment and circuit. About the structure, holder and tunnel have been made. Holder is used to place the transducers face to face and tunnel is to make homogenous wind. For equipment, theoretical anemometer has been changed. The first anemometer used to measure the theoretical wind speed is cup-type and the resolution is 0.1 m/s. In order to improve the accuracy, a scientific thermal anemometer whose resolution is 0.01 m/s is used. And the change to circuit is filter. Filter is designed to eliminate the ripples and decrease the timing jitter.

5.2 Recommendation

For later development, there are two ways to improve this anemometer.

The first is to focus on the accuracy of the one-dimensional anemometer. In order to improve the accuracy, the received signal must be more stable. Choose better transducers so the efficient is higher or build better construction so that there will be less turbulence. Another way is to change the one-dimensional anemometer to two-dimensional or three-dimensional. In order to do this, more transducers are needed.

If somebody wants to redo this study, the advice is to decrease the possible wind turbulence as much as possible because it is has the biggest influence to the received signal.
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Appendix A: Speed of sound formula comparison

\[
x = [-49:1:50];
q = 1 + x/273.15;
y = 331.3 \cdot q^{(1/2)};
\]

plot (x,y,'red')
grid on
hold on
z = 331.3 + 0.606 \cdot x;
plot (x,z)

Fig. A. The speed of sound in different temperature using the two formulas
Appendix B: Ultrasonic transducer datasheet

Fig. B. The data sheet for the transducers
Appendix C: Propagation time in different wind and temperature

Tab. C. The propagation time in different wind speed and temperature

<table>
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<tr>
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