# Design of a 1-D Sonic Anemometer

## Mid-Course Design Review

ECE 415: Senior Design Project
Department of Electrical and Computer Engineering
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# Abstract

*This paper discusses a proposed design for a one-dimensional sonic anemometer. It will describe the background of the project and will examine the criteria and specifications that this design should achieve. It will provide a technical description of the proposed design, and will provide in detail the goals of this project. It also will contain information on our progress thus far and our intentions for the future.*

# Introduction

For the senior design project, we will be working with the University of Massachusetts Amherst Geosciences Department to design a one-dimensional sonic anemometer. This device, as suggested by Professor Jackson of the Electrical and Computer Engineering Department and Professor Voss of the Geosciences Department, measures small wind speeds by sending ultrasonic signals through the air between transducers. Once fully functional, the Geosciences Department will be able to use the instrument for their research.

The current design consists of a frequency generator that sends a sine wave to two transmitters. The transmitters will propagate the waves over a fixed distance and receivers will then capture the signals. The receivers then send the signal to the two comparators in order to convert it to digital logic, which can then be inputted to the Programmable Logic Device to perform the necessary calculations for wind speed. The result can then be displayed on LED's.

# Technical Description

### Initial Calculations

Before proceeding with the design, research in the theory and background of anemometers had to be understood in order to build a feasible project. Several equations were derived relating distance, time, and temperature to the speed of the signal.

$$v_{signal} = \frac{d}{t} \tag{1.1}$$

$$v_{signal} = 331.45(\sqrt{1+(T/273)}) \tag{1.2}$$

20ºC was chosen because this represented room temperature and the velocity of the signal was found to be 343.376 m/s, assuming zero wind speed. From here it was easy to calculate the time it took for the sine wave to travel from the transmitter to the receiver. Ultimately, the desired specification was to measure wind speeds as slow as 1 mm/s, so given this constraint, it was a good starting point for acquiring component parameters. The following equations show how this constraint affects the components.

$$v_1 = v_{signal} + v_{wind} \tag{1.3}$$

$$v_2 = v_{signal} - v_{wind} \tag{1.4}$$

$$v_1 - v_2 = 2 \cdot v_{wind} \tag{1.5}$$

$v_2$ was set to be 343.376 m/s and $v_1$ to be .002 m/s greater than $v_1$ in order to get a 1 mm/s wind speed. From here $t_1$ and $t_2$ were calculated.

$$v_1 = \frac{d}{t_1} = 343.378 m/s = \frac{1.06m}{t_1} \tag{1.6}$$

$$v_2 = \frac{d}{t_2} = 343.376 m/s = \frac{1.06m}{t_2} \tag{1.7}$$

The absolute time for the signal to travel from speaker one to receiver one is 3.08697 ms and the time for speaker 2 to receiver 2 is 3.08699 ms. Using this, the counter frequency can be derived.

$$\Delta t = t_2 - t_1 = 17.9801 ns \tag{1.8}$$

$$f = \frac{1}{T} = \frac{1}{\Delta t} = \frac{1}{16.962 ns} = 58.95 MHz \tag{1.9}$$

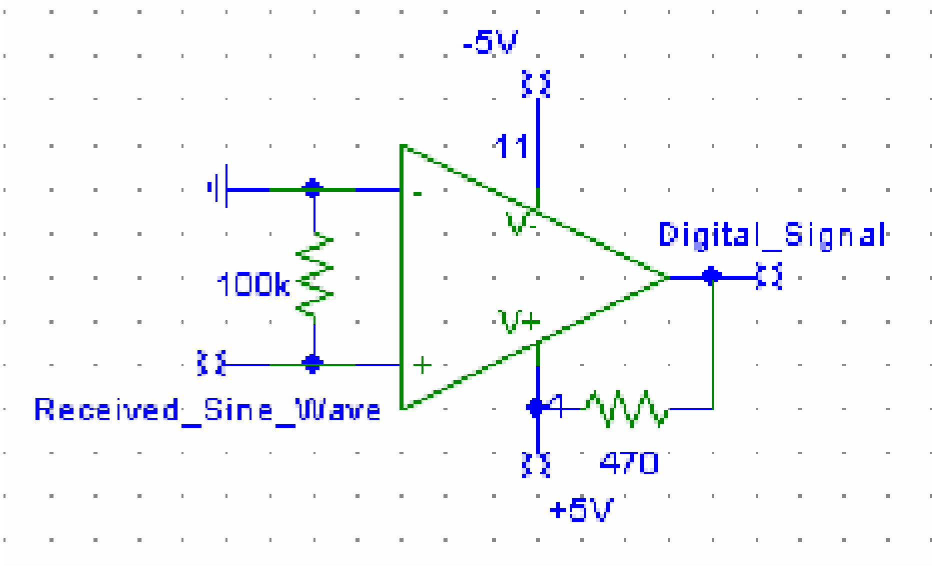
In the future, the counter will calculate a time difference that can be stored and inputted into a controller containing an algorithm that will calculate wind speed. A minimum of 27 bits is needed for the counter frequency.

### Zero Crossing Detector

The next step was to figure out how to decipher the received sine waves in such a way that $\Delta t$ could be extracted. It will be proven later why only $\Delta t$ needs to be extracted from the signals. The zero crossing detector was extremely important because the difference in zero crossings, where the amplitude of the sine wave is zero, will remain constant regardless of amplitude fluctuations. Converting the analog signal to a digital signal was performed using a LM339 comparator, where a logic HIGH was 5 volts when the amplitude of the sine wave was greater than or equal to 0, and a logic LOW was 0 volts when it was negative. The LM339 comparator will be discussed more thoroughly in the following section. The output of the comparator is a pulse whose width will not vary due to amplitude fluctuations. It was necessary to use this method because the inherent side winds in the system cause the amplitudes to vary sporadically.

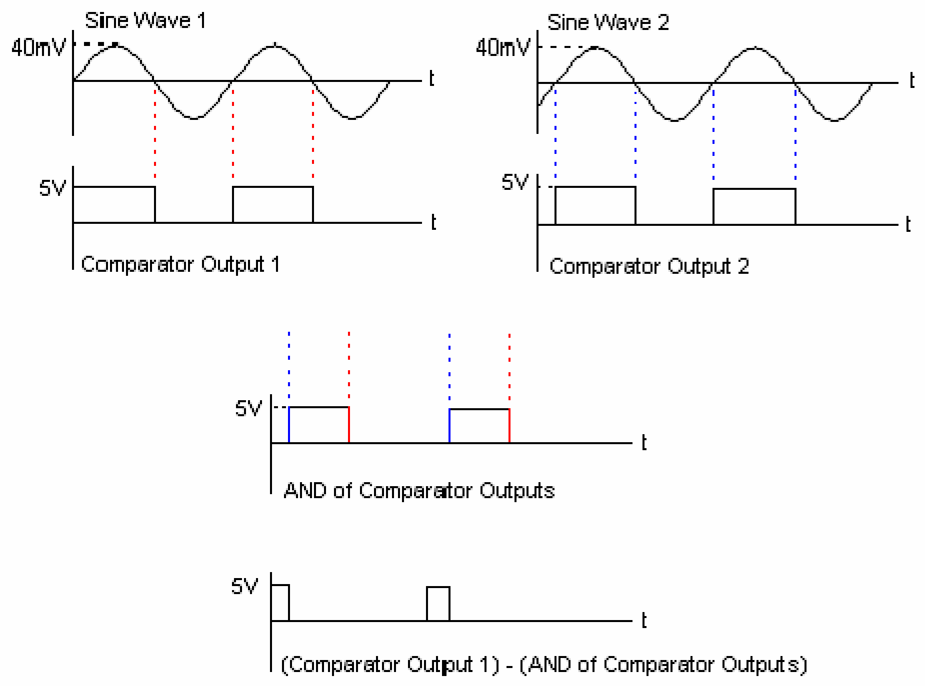
## Comparator

In order to determine the difference in locations of the zero crossings for each wave, the sine wave was converted to digital signals by comparing the wave's amplitude to ground. The rising and falling edge of the comparator's output pulse indicates the location of the zero crossings. The LM741 chip was tested first as a comparator, but the optimal chip is the LM339 due to its smaller delay time and high frequency operation. It was necessary to choose a comparator that could operate at high frequencies since the transducers send a 40.2 kHz sine wave, which will be explained in more detail later on. The comparator was wired on a breadboard using the spec sheet as a guide, but there was an additional 100-kΩ resistor that was added so as to provide a bias current to the base of the BJT at the positive input.



One complication that arose in this area was that a large offset voltage occurred because the receiver had a very large impedance, and the BJT at the positive input required a small bias current to operate. This small bias current, when multiplied by the impedance of the transducer, lead to a large voltage at the positive input of the comparator. Since there was only a small voltage at the negative input, this caused quite a large voltage offset that could not be fixed using potentiometers and a voltage supply. This offset caused the comparator to compare to a value slightly larger than zero, rather than comparing the received signal to ground. Because side winds caused amplitude variations, a value just above zero was not consistently in the same location, and the duty cycle of the digital signal varied slightly. This will later be remedied by using a comparator that has a CMOS input.

Once each sine wave had been converted to a digital signal, necessary steps to find the phase difference between the two received waves took place. By taking the AND of the two digital signals and then subtracting that result from the width of the original pulse yielded a final pulse that would indicate the width of $\Delta t$ which would be used to calculate wind speed.



## Comparator Theory

As previously discussed in initial calculations, there existed two waves, $v_1$ and $v_2$, where $v_1$ was traveling faster than $v_2$. These two waves were offset by a total phase difference of $\Delta t$, where $v_1$ was offset $\frac{\Delta t}{2}$ to the left, and $v_2$ was offset $\frac{\Delta t}{2}$ to the right.

$$v_1 = v_{signal} + v_{wind} = \frac{d}{t - \frac{\Delta t}{2}} \tag{1.10}$$

$$v_2 = v_{signal} - v_{wind} = \frac{d}{t + \frac{\Delta t}{2}} \tag{1.11}$$

By subtracting $v_2$ from $v_1$, an equation was derived that related $v_1$, $v_2$, and the velocity of the wind.

$$2 \cdot v_{wind} = v_1 - v_2 = \frac{d}{t - \frac{\Delta t}{2}} - \frac{d}{t + \frac{\Delta t}{2}} \tag{1.12}$$

$$2 \cdot v_{wind} = d \cdot \left( \frac{1}{t - \frac{\Delta t}{2}} - \frac{1}{t + \frac{\Delta t}{2}} \right) \tag{1.13}$$

Once this relationship was found, properties such as the one below were used to simplify the wind equation.

$$\text{if } x << 1, \text{ then } \frac{1}{1\text{-x}} \approx 1 + x. \tag{1.14}$$

Simplifying the equation using this fact, a finalized equation was produced.

$$2 \cdot v_{wind} = \frac{d}{t}\left[1 + \frac{\Delta t}{2t} - \left(1 + \frac{-\Delta t}{2t}\right)\right] \tag{1.15}$$

$$2 \cdot v_{wind} = \frac{d}{t}\left(\frac{\Delta t}{t}\right) \tag{1.16}$$

$$v_{wind} = \frac{d}{2t}\left(\frac{\Delta t}{t}\right) = \frac{v_{signal}^{\;2}}{2d}\Delta t \tag{1.17}$$

.

$$v_{wind} = \frac{v_{signal}^{\;2}}{2d}\Delta t \tag{1.18}$$

This equation related the wind's velocity to $\Delta t$, and only depended on $\Delta t$. All other values were constants or predetermined values.

For example,

$$\begin{aligned} &\text{for } v = 343.37\ m/s,\ \Delta t = 17.9801 ns \\ &v_{wind} = \frac{343.37^2}{2 \times 1.06} \cdot 17.9801 \cdot 10^{-9} \\ &v_{wind} = 1\ \ mm/s \end{aligned} \tag{1.19}$$

This proved that all that was needed in order to find the wind speed was $\Delta t$.

**Transducers**

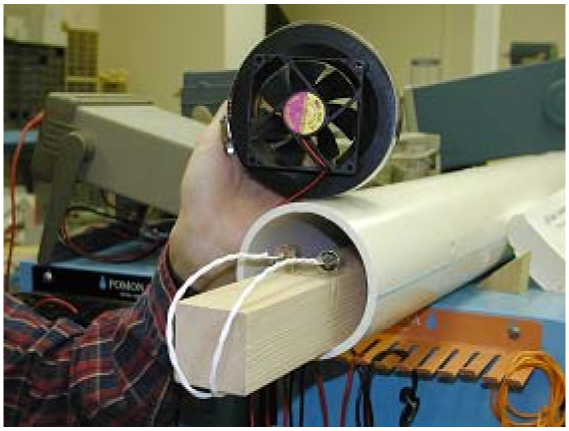
For the design, the target was to choose an audible frequency range. Cost and familiarization of transducers limited the choices. The transducers used in the design were Panasonic P9895-ND (transmitter) and P9894-ND (receiver). These transducers operate at a nominal frequency of 40.0 kHz. The temperature range of these transducers is –40 to 100ºC. The temperature range was ignored at this point in the design process; however, it will play a significant role in the final design.

Two pairs of transducers were mounted at a fixed distance apart from each other. Each pair consisted of a transmitter and a receiver. Each transmitter from each pair would propagate a sine wave, which would be analyzed to calculate $\Delta t$.

The actual experimental apparatus results were consistent with the manufacturer's data sheet. The optimal frequency with an input sine wave of $10V_{P\text{-}P}$ generated the maximum received signal of $40mV_{P-P}$. Initially, the idea was to use a burst or pulse signal. Both of these introduced dispersion. This caused other frequencies to propagate faster than the 40 kHz signal resulting in unwanted noise. Thus, the continuous sine wave was used.

Next semester bi-directional transducers will be implemented. This will involve adding circuitry for switching the transducers from transmit to receive. These transducers are also higher in cost, but greatly reduce or eliminate any angles that are off-center. This off-center angle can cause transducers to misread undetectable wind speeds. More research will be required to find an optimal frequency that will work for the range of wind speeds that are dictated by the Geosciences department.

## Test Setup



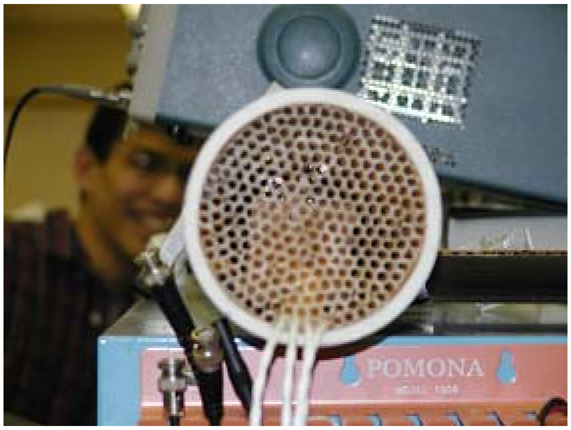
To test the sonic anemometer, a wind tunnel was developed to reduce crosswinds. These crosswinds affected the amplitude of received signals. This fluctuation caused the zero detector to have a varying width which also caused a flux in the $\Delta t$.

A DC fan was used to create the airflow. This is the same type of fan used in a desktop computer case for ventilation. The airflow was pulled through the pipe, and the slowest measured wind speed was 25 cm/s. Unfortunately, this wind speed was not anywhere close to the desired 1 mm/s.

The next part of the test setup was the PVC Drain Pipe. The pipe had a four-inch diameter and was 84 inches in length. The purpose of the PVC was to eliminate crosswinds and direct the flow pulled by the wind across both pairs of transducers.

The transducer setup consisted of a pine board, CD case, straws, and the twisted pair insulated wire. The dimensions of the pine board were 6 feet by 4 square inches. There were slots cut every 5 inches, which were spaced arbitrarily.

The transducers were mounted onto the pine board using CD casing. The purpose for using this was the fact that it was non-conductive and rigid. Since the transducers had conductive posts, this non-conductive property was vital. The CD case was placed in the slots on the pine board and supported with straws. In the experiments, a distance of 1.06 meters was used as the distance between the transducers.

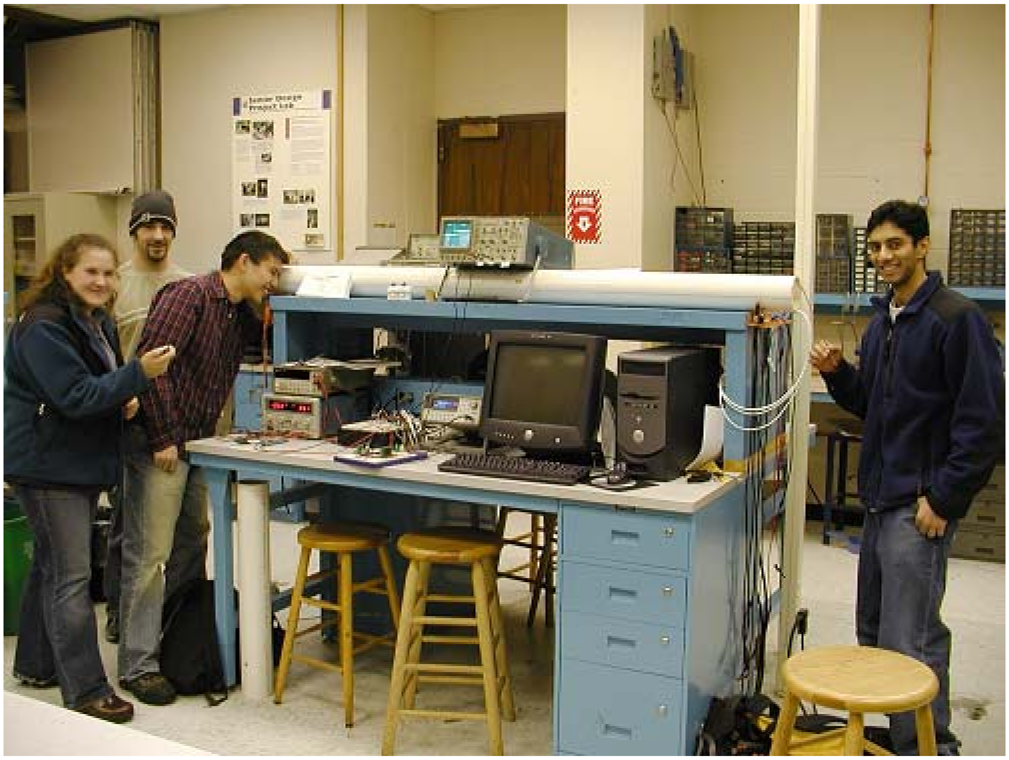


The other end of the PVC pipe had straws to cut down swirling and turbulence. After testing the setup it was determined that straws need to be in both ends of the pipe because of turbulent affects near the fan. In theory, having straws in both ends would eliminate all swirling within the tunnel. The board would introduce some turbulence, but minimal in comparison with cross winds.

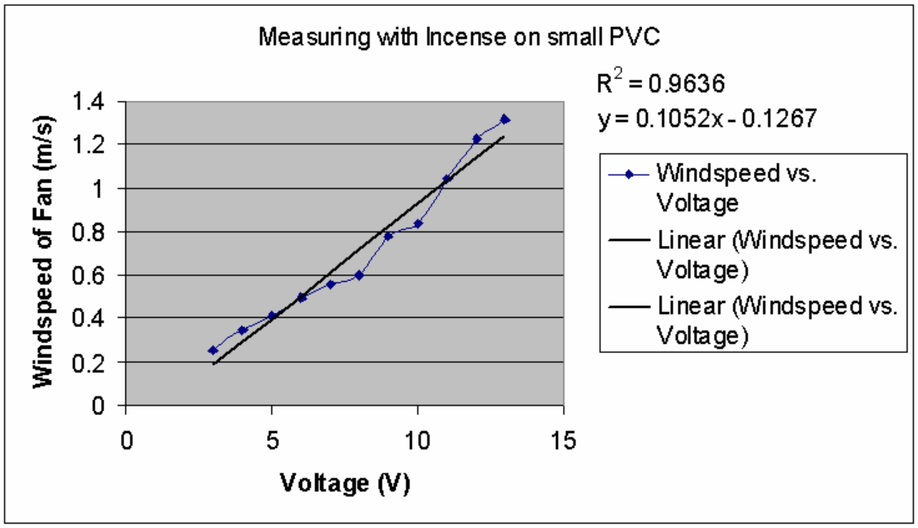
The final part of the setup was the twisted pair wire. The length and the insulation were important aspects in the wire. If there were variations in lengths of wire, there could have been a time delay, which would be interpreted as an undetectable wind speed. This could be accounted for by testing zero wind speed. The metal insulation binding the wire eliminated most if not all of the noise introduced from system surroundings.

## Wind Flow Testing Part I

The anemometer was unique because it was capable of measuring small wind speeds. In order to test the device, precise measurements of the actual wind speed produced by the fan in the wind tunnel needed to be found using another method. The easiest technique was to use a smoke test. This was done by first drilling a small quarter inch hole near the fan end of the PVC pipe and pointing a laser beam into it. Another quarter inch hole was drilled perpendicular to that one so the laser beam could be seen. 90º was most desirable because this was where there would be the maximum reflected waves coming off of the smoke. The interior part of the PVC pipe surrounding the two drilled holes was completely filled with black, non-reflective paper so there would be no stray photons being noticed. Once the setup was completed, incense was lit at the right end of the pipe and a stopwatch was used to time the duration of travel distance from when the smoke entered to the pipe to when it could be visible by the laser. The laser would be clearly visible due to the fact that photons would reflect off of the smoke particles, and the laser beam would appear to be a continuous stream of light through the smoke. Once the viewer saw the laser beam, the timekeeper was alerted to stop the stopwatch. There was some human error with this method, but several trials were implemented, and the finalized results would be the average of all the trials. This method turned out to be quite successful. The wind speed varied linearly with the voltage supplied to the fan. The following picture shows the setup of the equipment with Chethan generating the smoke, Michael watching for the laser beam, Vanessa keeping time, and Robert varying the voltage of the fan.

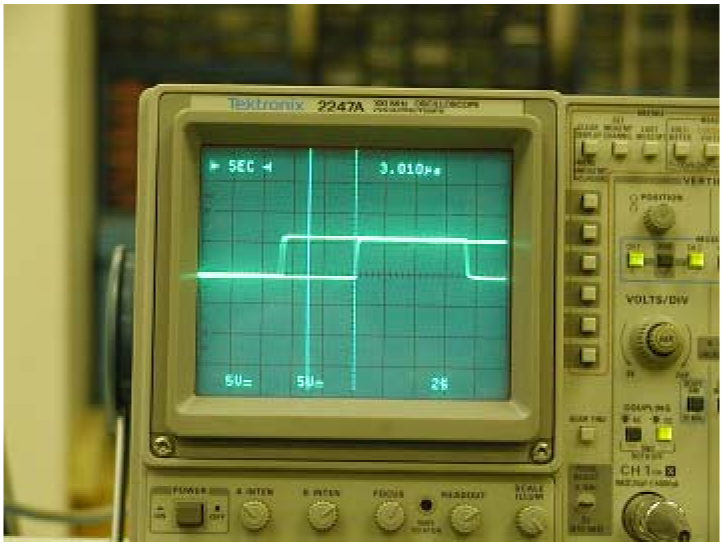


The following graph shows the linear relationship between the voltage supplied to the fan and the measured wind speed. For all the charts below see **Appendix 1** for experimental data.

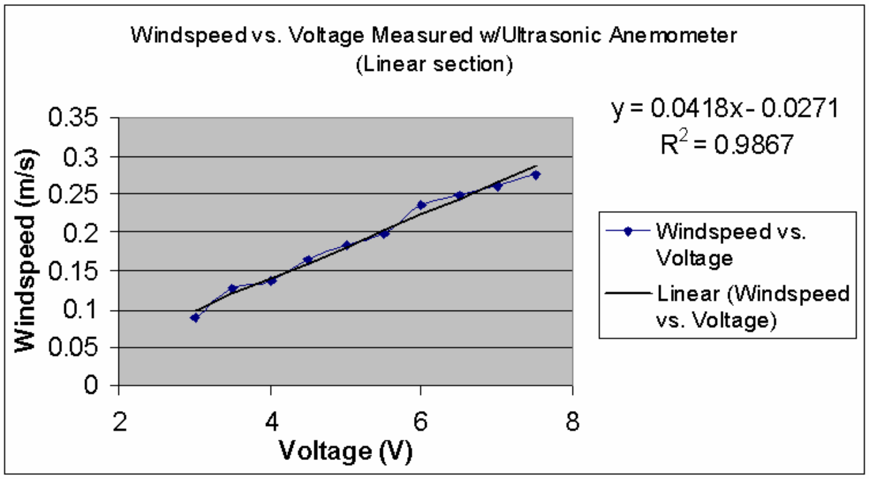


# Wind Flow Testing Part II

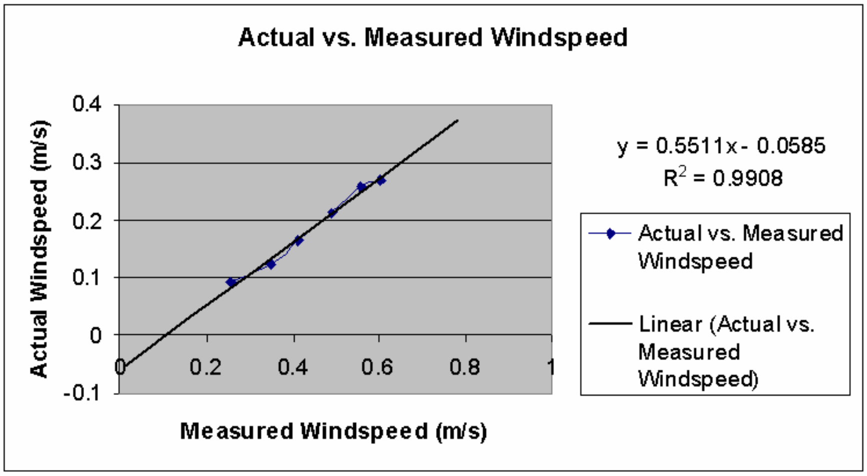
This phase in the design dealt with testing the anemometer to see if the measured $\Delta t$ on the scope was actually the wind speed created by the fan. The voltage supplied to the fan was from 3 to 7 volts and measurements of $\Delta t$ were taken every .5 volts. $\Delta t$ was measured on the scope by lining up the first cursor line on the scope to correspond to the rising edge of the first pulse and the second cursor line to the second pulse. The following picture of the oscilloscope shows how $\Delta t$ was read:



These measurements were then plotted versus the voltage supplied to the fan.

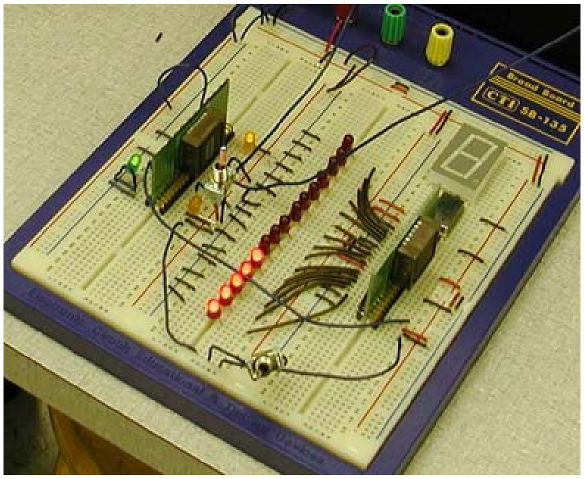


From this graph, it was apparent that there existed a linear relationship. This same linear relation was observed when wind speed vs. voltage was graphed. From this, assumptions could be made that there should be a linear relation between the wind speed measured with the smoke test and the wind speed measured with the anemometer. Even if there was some offset, the linearity of this showed that the anemometer did indeed function to a certain level of accuracy. The following graph shows the functionality of the anemometer.



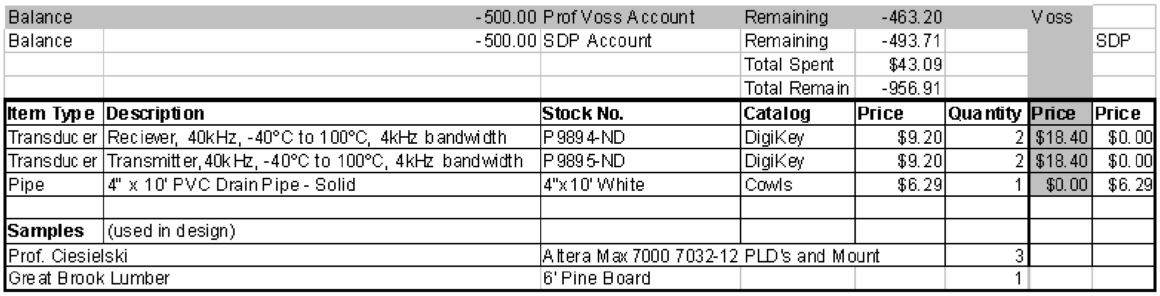
This shows that the initial calculations and tests were successful in showing a linear relationship. Any offset could be adjusted in the future.

## PLD/Counter



To calculate $\Delta t$, two Programmable Logic Devices (PLD), a 4 MHz clock, fifteen red LED's, two yellow LED's, and one green LED were used. The PLD's were programmed in VHDL and mounted onto a breadboard. The left PLD acted as the counter trigger, and also showed the direction of the wind. The direction was indicated by the yellow LEDs. The green LED would go HIGH when all data was acquired. The red LED's showed the count from the counter, which was clocked at 4 MHz. The count will fluctuate depending on the frequency of the clock.

# Expenses



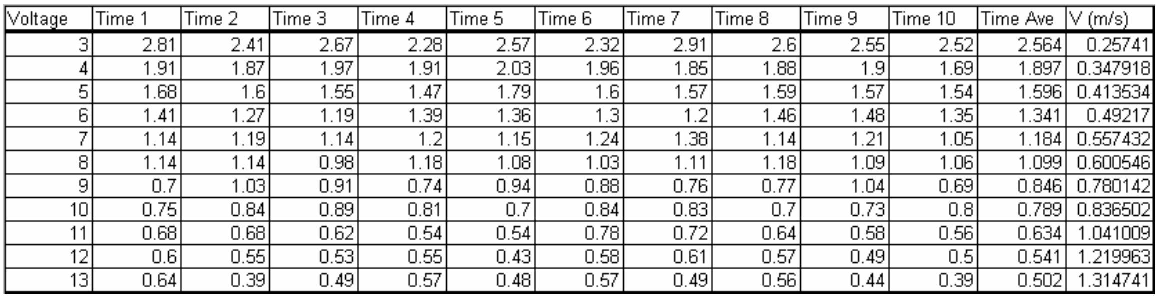
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Balance | -500.00 | Prof Voss Account | Remaining | -463.20 | | Voss | |
| Balance | -500.00 | SDP Account | Remaining | -493.71 | | | SDP |
| | | | Total Spent | $43.09 | | | |
| | | | Total Remain | -956.91 | | | |
| **Item Type** | **Description** | **Stock No.** | **Catalog** | **Price** | **Quantity** | **Price** | **Price** |
| Transducer | Reciever, 40kHz, -40°C to 100°C, 4kHz bandwidth | P9894-ND | DigiKey | $9.20 | 2 | $18.40 | $0.00 |
| Transducer | Transmitter, 40kHz, -40°C to 100°C, 4kHz bandwidth | P9895-ND | DigiKey | $9.20 | 2 | $18.40 | $0.00 |
| Pipe | 4" x 10' PVC Drain Pipe - Solid | 4"x10' White | Cowls | $6.29 | 1 | $0.00 | $6.29 |
| | | | | | | | |
| **Samples** | (used in design) | | | | | | |
| Prof. Ciesielski | | Altera Max 7000 7032-12 PLD's and Mount | | | 3 | | |
| Great Brook Lumber | | 6' Pine Board | | | 1 | | |

Out of a total of $1,000, $43.09 has been spent this semester on components and parts for the project. Many of the devices were samples from various manufacturers. Other materials were supplied by members of the group or were found within the SDP lab.

# Conclusion

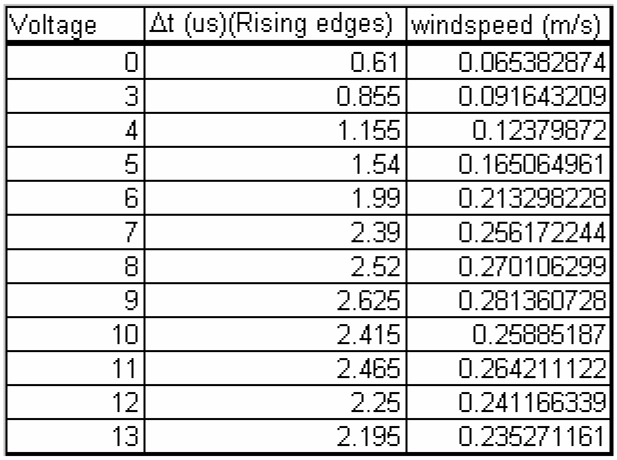
This semester the MDR specifications were met accordingly. Small wind speeds were calculated down to 25 cm/s. Experimental data was also compared to actual data in order to show a linear relationship. Nevertheless, improvements on the design still need to be made on the anemometer. For Spring 2004, more accurate methods of finding wind speed are in affect. Some ideas that are circulating among the design team include replacing the PLD with a PIC controller and a counter IC, using bi-directional transducers with switching circuitry instead of monodirectional transducers, and possibly integrating CMOS input comparators that will replace the existing BiCMOS comparators. The final design will hopefully comprise of a working anemometer, which will be able to measure wind speeds of 1 mm/s.

# Appendix 1



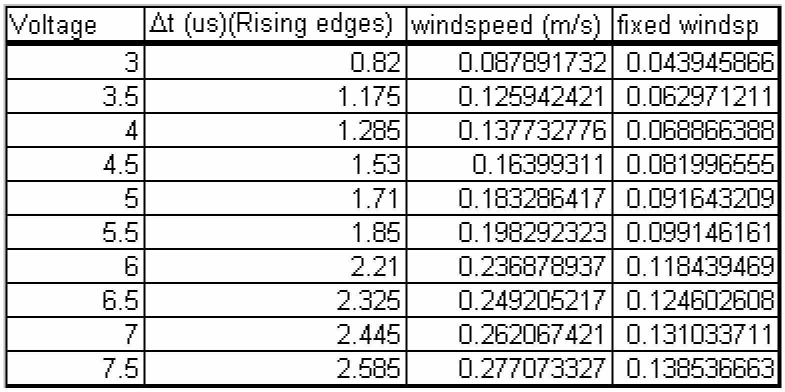
| Voltage | Time 1 | Time 2 | Time 3 | Time 4 | Time 5 | Time 6 | Time 7 | Time 8 | Time 9 | Time 10 | Time Ave | V (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 2.81 | 2.41 | 2.67 | 2.28 | 2.57 | 2.32 | 2.91 | 2.6 | 2.55 | 2.52 | 2.564 | 0.25741 |
| 4 | 1.91 | 1.87 | 1.97 | 1.91 | 2.03 | 1.96 | 1.85 | 1.88 | 1.9 | 1.69 | 1.897 | 0.347918 |
| 5 | 1.68 | 1.6 | 1.55 | 1.47 | 1.79 | 1.6 | 1.57 | 1.59 | 1.57 | 1.54 | 1.596 | 0.413534 |
| 6 | 1.41 | 1.27 | 1.19 | 1.39 | 1.36 | 1.3 | 1.2 | 1.46 | 1.48 | 1.35 | 1.341 | 0.49217 |
| 7 | 1.14 | 1.19 | 1.14 | 1.2 | 1.15 | 1.24 | 1.38 | 1.14 | 1.21 | 1.05 | 1.184 | 0.557432 |
| 8 | 1.14 | 1.14 | 0.98 | 1.18 | 1.08 | 1.03 | 1.11 | 1.18 | 1.09 | 1.06 | 1.099 | 0.600546 |
| 9 | 0.7 | 1.03 | 0.91 | 0.74 | 0.94 | 0.88 | 0.76 | 0.77 | 1.04 | 0.69 | 0.846 | 0.780142 |
| 10 | 0.75 | 0.84 | 0.89 | 0.81 | 0.7 | 0.84 | 0.83 | 0.7 | 0.73 | 0.8 | 0.789 | 0.836502 |
| 11 | 0.68 | 0.68 | 0.62 | 0.54 | 0.54 | 0.78 | 0.72 | 0.64 | 0.58 | 0.56 | 0.634 | 1.041009 |
| 12 | 0.6 | 0.55 | 0.53 | 0.55 | 0.43 | 0.58 | 0.61 | 0.57 | 0.49 | 0.5 | 0.541 | 1.219963 |
| 13 | 0.64 | 0.39 | 0.49 | 0.57 | 0.48 | 0.57 | 0.49 | 0.56 | 0.44 | 0.39 | 0.502 | 1.314741 |

**Table 1. Data for measuring w/Incense on Small PVC**



| Voltage | Δt (us)(Rising edges) | windspeed (m/s) |
|---|---|---|
| 0 | 0.61 | 0.065382874 |
| 3 | 0.855 | 0.091643209 |
| 4 | 1.155 | 0.12379872 |
| 5 | 1.54 | 0.165064961 |
| 6 | 1.99 | 0.213298228 |
| 7 | 2.39 | 0.256172244 |
| 8 | 2.52 | 0.270106299 |
| 9 | 2.625 | 0.281360728 |
| 10 | 2.415 | 0.25885187 |
| 11 | 2.465 | 0.264211122 |
| 12 | 2.25 | 0.241166339 |
| 13 | 2.195 | 0.235271161 |

**Table 2. Data for Wind speed vs. Voltage w/Ultrasonic Anemometer**



| Voltage | Δt (us)(Rising edges) | windspeed (m/s) | fixed windsp |
|---|---|---|---|
| 3 | 0.82 | 0.087891732 | 0.043945866 |
| 3.5 | 1.175 | 0.125942421 | 0.062971211 |
| 4 | 1.285 | 0.137732776 | 0.068866388 |
| 4.5 | 1.53 | 0.16399311 | 0.081996555 |
| 5 | 1.71 | 0.183286417 | 0.091643209 |
| 5.5 | 1.85 | 0.198292323 | 0.099146161 |
| 6 | 2.21 | 0.236878937 | 0.118439469 |
| 6.5 | 2.325 | 0.249205217 | 0.124602608 |
| 7 | 2.445 | 0.262067421 | 0.131033711 |
| 7.5 | 2.585 | 0.277073327 | 0.138536663 |

**Table 3. Data for Wind speed vs. Voltage w/Measured Ultrasonic Anemometer**