Measuring the Air Speed Created in a Wind Tunnel

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1 Abstract

The Pomona Physics department possesses a wind tunnel which was constructed as part of a past student's thesis project. I have improved the wind tunnel by adding to it a device which measures the air speed within the tunnel and displays this speed conveniently on an LCD screen. This should allow the device to be better used for future experiments in the department.

2 Introduction

2.1Background

The first enclosed wind tunnels were invented in 1871. Since then the wind tunnel has been used to test many of the modern conveniences which have become essential to our lives today. It has helped man take to the sky in airplanes. It has helped to keep our tall buildings and expansive bridges safe from collapsing under unforgiving winds. It has allowed the car industry to create sleeker and more power efficient designs. The wind tunnel has been a basic and essential tool in the study of aerodynamics.

Aerodynamics is an inherently difficult subject of study. Air is a gaseous mixture of various particles, molecules, and tiny compounds. These bits are all flying around freely and constantly bumping into one another. It is the task of the field of aerodynamics to understand the movement of this mixture and how it interacts with various objects. Thanks to tools like the wind tunnel, the movement of air around objects and the effects of such movements have become well understood in a generalized manner. We know how planes fly and what shapes are aerodynamically efficient. We also have determined an expression for how air moves around simple shapes such as spheres and disks. Things become more difficult, however, when attempting to model the airflow around anything other than the most basic of shapes. This is why the wind tunnel is an essential tool. It allows the simulation of circumstances with which the experimenter may be concerned.

A good example of the essential role which the wind tunnel plays is that of the wiffle ball. A skilled wiffle ball pitcher can make a ball move in all sorts of seemingly physics-defying flight paths in which the ball may fly in an extremely curved path before hitting its target. The fact that the ball is hollow and possesses holes allows the wiffle ball to achieve this kind of unexpected behavior. An object that appears to be just a simple sphere is suddenly made into a challenging aerodynamic problem simply by adding a few small holes to its surface that open into a hollow interior. It was not until relatively recently that this phenomenon was understood and the wind tunnel was an integral part to discovering its cause. Any assertion having to do with the aerodynamic properties of a wiffle ball was purely speculation before these properties could be directly observed and studied inside a wind tunnel.

2.2 Motivation

My motivation for this project is of course to fulfill my thesis requirement for the physics major and to have a valuable learning experience. The motivation for this project in particular is to provide the department with a wind tunnel which it can use in future experiments. The wind tunnel was originally created to be used as part of a lab in which students would calculate the forces on a ping pong ball in air flow. My goal is to have the tunnel be available for use for a wider range of purposes. It could be modified to be once again used to teach students about fluid dynamics. It also has the potential to aid in the understanding of the aerodynamics involved in future student projects. In addition, It is my aim to keep this as a relatively cheap alternative to manufactured wind tunnels which can cost several thousands of dollars. Having been made by a student also keeps the design relatively simple and its design easily understood. This allows it to be more easily modified without fear of damaging complex and expensive equipment which may be difficult to replace or repair.

2.3 Equipment

The wind tunnel was originally constructed by Eugene S. Stokes Jr. in ’65. The main body of the wind tunnel is made of aluminum. It has a total length of about 7.5 feet. The test chamber (Figure 1A) was constructed using an aluminum pipe 11.5 inches in diameter and 36 inches long. A 17 inch section was cut away at the middle of the top of the pipe and replaced with a piece of plexiglass (Figure 1B). This allows the test chamber to be viewed while the wind tunnel is operating while still keeping the air flowing through relatively uniformly. The piece of plexiglass is also easily removed allowing access to the test chamber. On either side of the aluminum pipe which constitutes the test chamber there are two pieces which flare outwards to about 20 inches in diameter (Figure 1C). This test chamber portion is supported by a simple wooden base (Figure 1D).

The air is pushed through the tunnel by a “Trade Winds” squirrel cage fan (Figure 1E). This fan is run by a 1/3 horsepower electric motor (Figure 1F). The fan is connected to the tunnel using a plywood disc cut to fit the mouth of the fan. The diameter of the disc is such that it just fits into the tunnel. This disc has foam glued to its outer rim thus creating a seal between the fan and the tunnel, helping to keep the vibrations of the fan and motor from transferring too heavily to the tunnel. The portion of pipe constituting the test chamber closest to the fan was originally filled with a honeycomb of asbestos in order to straighten the airflow from the fan. This has since been replaced by straws (Figure 2). The motor and fan are mounted to a separate small piece of plywood (Figure 1G). The motor is controlled by a motor controller (Figure 1H) purchased from Minarik Electric Company. It features a simple dial for control of the motor speed, an on/off switch, and plugs into an outlet.

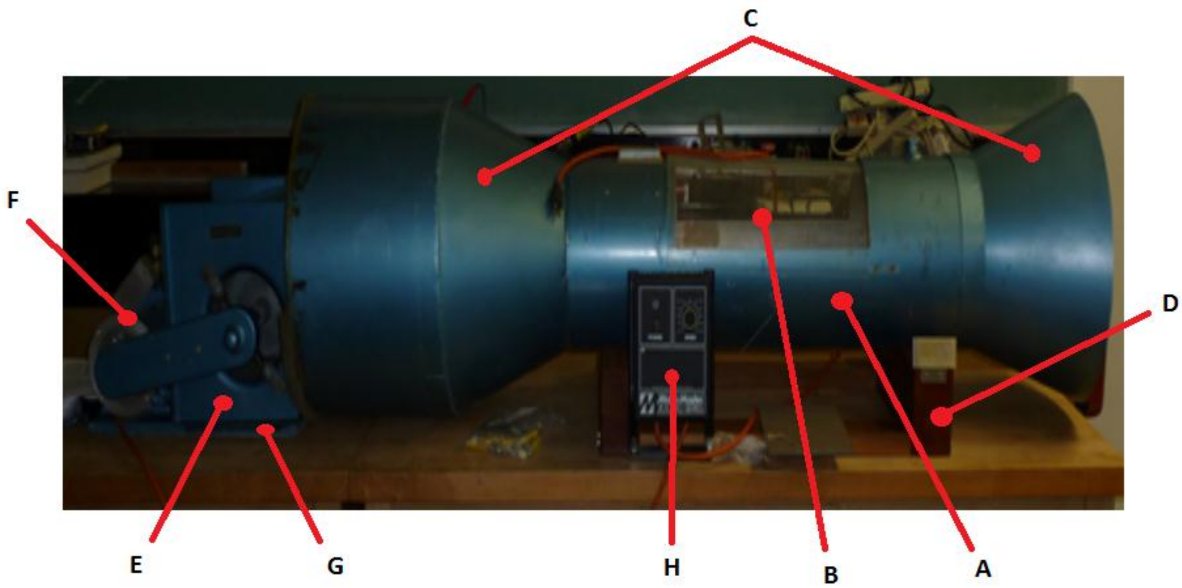
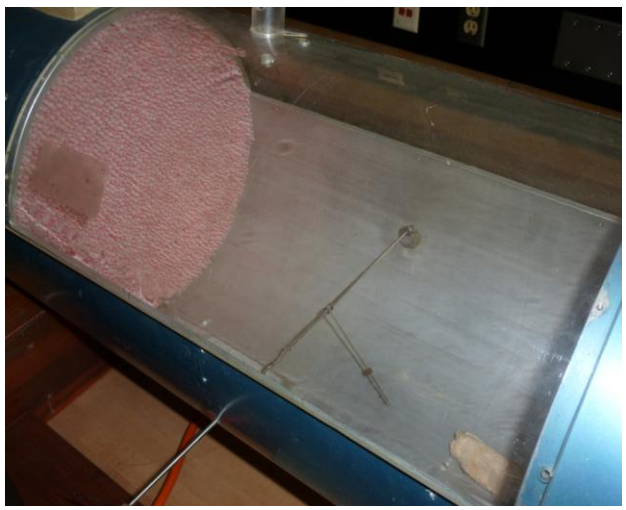


Figure 1. Wind Tunnel.

(A) Test Chamber
(B) Plexiglass Viewing Section
(C) Flared Ends
(D) Wooden Base
(E) Fan
(F) Motor
(G) Plywood Base
(H) Motor Controller

Figure 2. Test Chamber

This is the testing area of the wind tunnel. The honeycomb of straws can be seen in the upper left corner.



3 Theory

3.1 Anemometers

An anemometer is a device that is used to measure air speed. There are various types of anemometers, each with a different set of pros and cons associated with their method of measurement. Certain anemometers are more suited for some jobs than others, and not all of them are practical for use in a wind tunnel.

3.1.1 Cup and Windmill Anemometers

The most basic anemometers are cup and windmill anemometers (Figure 3). The air blows into their cups or blades and causes them to turn. The speed of the air is simply a function of the speed at which the cups or blades rotate. Cup and Windmill anemometers are simple and useful to setup outside when trying to simply measure wind speed. The cheapest and most basic handheld anemometers are also of this type.

Figure 3. Cup and Wind Anemometers

(Left) Cup Anemometer, (Middle) Windmill Anemometers, (Right) Handheld Anemometer

3.1.2 Tube Anemometer

This type of anemometer uses a measurement of pressure to determine air speed. A small tube containing liquid is used. One of them is parallel to the air flow and the other is perpendicular to it. The air flow causes small changes in the pressure in the section of the tube which is perpendicular to the air flow. This causes a shift in the liquid in the tube. This change can be translated into the air speed.

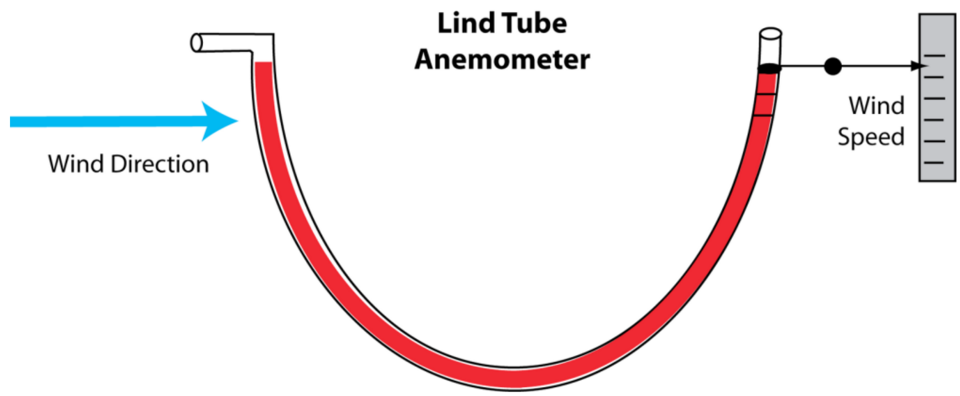


Figure 4. Tube Anemometer

The air moves as shown and creates a change in pressure which results in a air speed measurement.

3.1.3 Sonic Anemometer

A sonic anemometer uses ultrasonic waves to measure air speed and direction. Sound propagates through the vibrations of particles in the air. Several transducers on the anemometer emit and read ultrasonic waves. Sonic waves naturally propagate in a spherical wave in a uniform atmosphere. If the surrounding air is moving at some velocity then the center of the spherical wave will move at that same velocity. The sonic anemometer detects this movement in the spherical wave and translates it into an air speed value.

The sonic anemometer finds good use in places like weather stations. It is a more advanced and sophisticated alternative to the cup and windmill anemometers. It has a comparatively high temporal resolution. It is also very durable and has no moving parts to worry about. It does, however, need to be placed in the center of flow where it can affect the flow of air making it impractical for many other applications. It can also be affected by things which affect the speed of sound such as temperature, humidity, and pressure.

Figure 5. Sonic Anemometer

Theses transducers send and receive sonic signals.

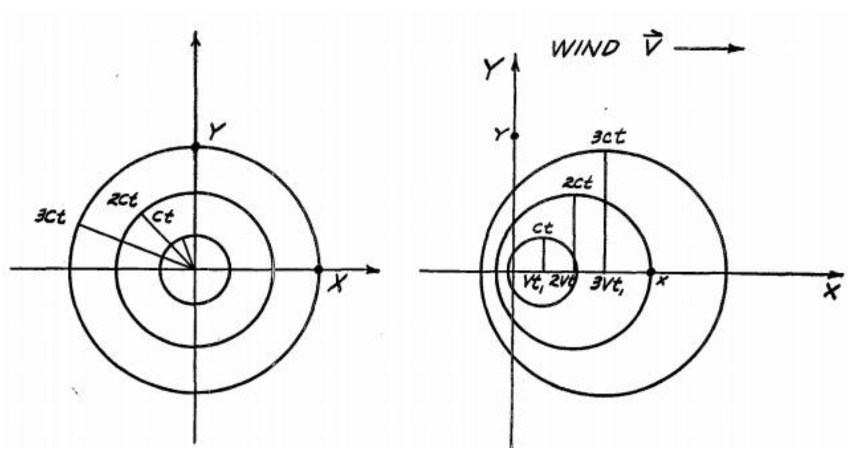


Figure 6. Illustration of the principle behind sonic anemometers

(Left) A stationary sound wave propagating outwards (Right) Sound wave moving with the air it is propagating moving in the positive x direction

3.1.4 Acoustic Resonance Anemometer

An acoustic resonance anemometer also uses sound waves to measure air speed and direction. It creates a resonating, standing wave inside a small cavity. Air flow through the cavity creates a phase shift in the sound waves. This allows the anemometer to measure air speed.

The acoustic resonance anemometer is small and durable. It has no moving parts to worry about. Its small size also allows it to be easily heated so that it will not ice over if used outdoors in the cold. Like the sonic anemometer it can be affected by things which affect the speed of sound such as temperature, humidity, and pressure. However, if the sensor readjusts to keep resonance the sensor can continue to make good measurements. They can be less accurate than other types of anemometers due to precipitation and dust particles distorting the sound waves.

3.1.5 Laser Doppler Anemometer

A laser Doppler anemometer uses a laser, seeding particles, and the Doppler Effect to measure air speed. The seed particles are small, reflective particles that flow in the air current. The laser Doppler anemometer emits a laser and the laser light bounces off of the seed particles and back to the anemometer. The movement of the particles creates a Doppler shift in the laser light which is related to the speed of the particles. The anemometer detects the Doppler shift and outputs a value for the air speed.

3.1.6 Hot-Wire Anemometer

A hot-wire anemometer uses a thin heated wire to measure air speed. The wire is heated above ambient temperature. The air flowing over the wire cools it. The faster the air is flowing the faster the wire becomes cooled. The resistance of the wire is dependent on the temperature. This relationship between resistance and cooling allows the air speed to be measured.

We now refer to ohm's law:

$$V = I*R \quad (1)$$

The electronics are designed to keep one of these values constant. For example, if a circuit is designed to keep resistance constant, which is the same as keeping the temperature of the wire constant, then when the wire is cooled the resistance is lowered and the voltage is increased to heat the wire and return the resistance to its original value. On the other hand, if the air starts moving more slowly the voltage begins to drop because it no longer needs to heat the wire quite as much.

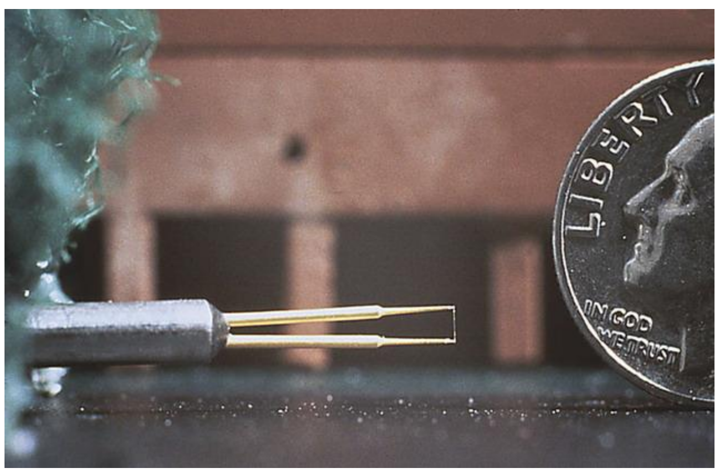


Figure 7. Hot-Wire Anemometer

The small, delicate wire measures air speed by measuring how much it is cooled.

Hot-Wire anemometers are delicate but precise. They can change quickly with the air speed and have high spatial resolution. They are therefore best used in situations where durability is not an issue, specific areas are to be measured and/or quick changes in air speed need to be observed.

3.2 Measuring the Motor

One method for measuring the speed of the air in the wind tunnel is by somehow finding the motor speed. The motor is the only source of air movement in the wind tunnel. This means that if the motor speed can be determined it can be directly correlated to the air speed in the tunnel and provide a method of measurement of said speed. The motor speed can, in turn, be determined by measuring the power going into the motor. If the power to the motor can be measured then it can be used to determine the air speed in the tunnel.

The motor controller is specifically designed to allow the operator to control the motor speed and therefore the air speed in the wind tunnel. This is done with a potentiometer. When the potentiometer is turned, the resistance that it provides is changed. When someone turns the dial, it simply changes the resistance of that potentiometer which changes the power going to the motor and changes the speed of the motor. By reading the resistance across the potentiometer a value can be assigned to the changing speed of the motor which in turn could be used to determine the air speed.

4 Design

4.1 Making a Few Adjustments

The wind tunnel is old and was in need of a few measures to tune it up. The belt connecting the fan to the motor was rather old. The covering for the belt was removed and the belt was replaced. Oil was also added to the fan. The foam around the plywood disc which connects the fan to the tunnel needed to be replaced. Foam was cut and glued to the rim of the disc. It was not a precise job but the foam compresses between the two pieces to fit so it should create an effective seal.

During the early stages of testing of the wind tunnel the motor would often violently shake when being accelerated. This led to the motor shaking itself and the fan off of the table. This hard fall caused the motor to become detached from the plywood into which it was screwed. The motor was then secured back into place using bolts for a strong attachment. It was also later found that the potentiometer on the motor controller which controlled the speed of the motor was not working properly. After the potentiometer was replaced, the motor accelerated in a much calmer manner. It no longer jolted when first ramping up to its target speed.

4.2 Anemometer

I decided to use a setup similar to that of the hot-wire anemometer. This design is fairly simple and allows for easy control with an Arduino. It uses a flow sensor which I purchased online. The circuit diagram is shown in Figure 8. The flow sensor is a small device which contains

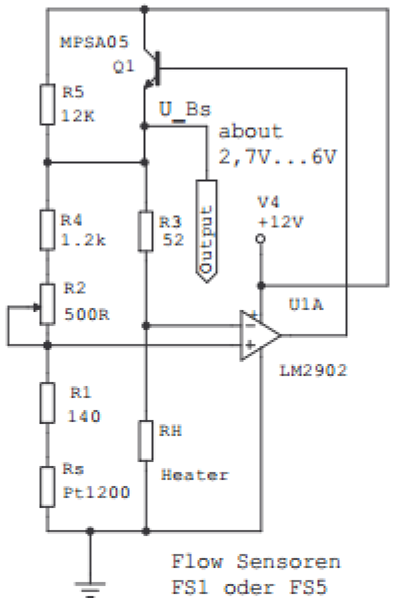


Figure 8. Circuit Diagram for Anemometer

This diagram was provided by the manufacturer of the flow meter. RH is the heating resistor. RS is the sensing resistor. The circuit changes the voltage to the heating resistor in order to keep the sensing resistor at a constant temperature. The output voltage directly related to the voltage sent to RH.

a small heating resistor and a sensing resistor. When the sensing resistor is cooled its resistance is changed. The circuit is designed to change the voltage going to the heating resistor in order to keep the sensing resistor at a constant temperature which translates into constant resistance. The circuit outputs a voltage based on the voltage put into the heating resistor. This gives a number for the relative heat being given off by the heating resistor which gives information regarding the cooling of the sensing resistor. This can then be used to find the air speed.

4.3 Measuring the Motor

The circuit used to measure the change of resistance in the potentiometer is shown in Figure 10. An Arduino Uno microcontroller was used for this project. The Arduino allows for the measuring of voltage. The voltage difference across the potentiometer is related to the resistance so measuring the voltage should yield the same relationship to air speed as the resistance. The potentiometer of the wiper was connected to the ground pin of the Arduino and the end of the potentiometer was connected to an analog input pin in order to measure the voltage across it. This causes the Arduino to use the wiper voltage as its reference voltage and causes the voltage reading in the analog input pin to yield the voltage across the potentiometer without further manipulation of the data. The 10k ohm resistor is used to limit the current being drawn away from the motor controller and to protect the Arduino from receiving more than it can handle. The motor controller runs off of the high voltages from the wall outlet and the Arduino only deals in small voltages (usually 0V – 5V) so if precautions aren't taken it could easily become overloaded and break. The capacitor consolidates a varying signal from the potentiometer with its charging and discharging behavior.

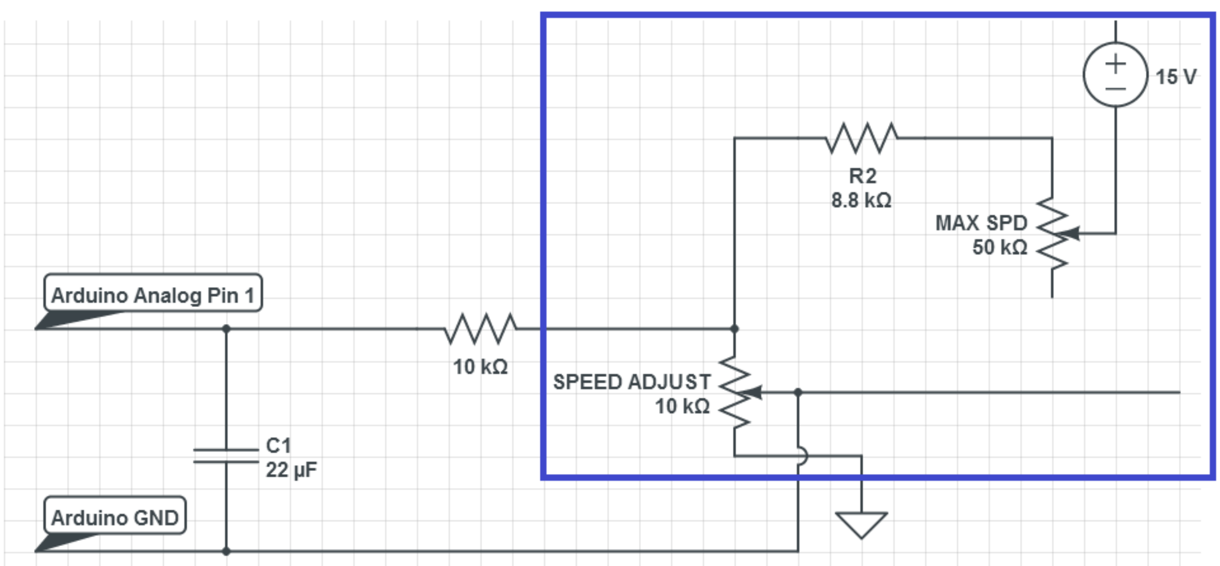


Figure 9. Circuit Diagram for Reading Motor Speed

This circuit measures the voltage difference between the wiper and one end of the potentiometer. The blue box shown corresponds to the blue box on the motor controller block diagram shown in Figure 10 which is found on the next page.

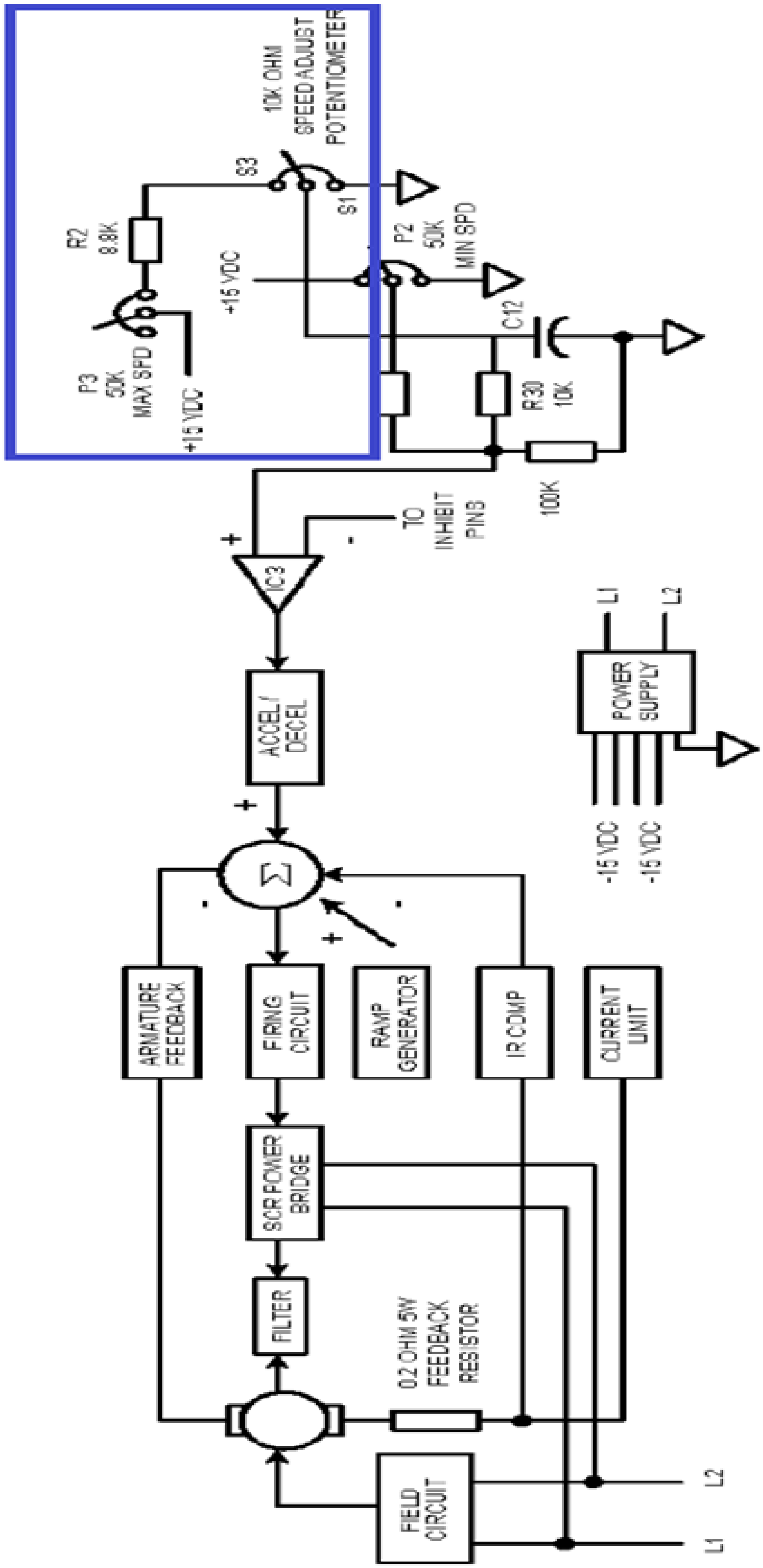


Figure 10. Block Diagram of Motor Controller Operation

The inner workings of the motor controller shown in a block diagram. The area of interest lies in the blue box. This box corresponds to the blue box in Figure 9. The potentiometer that is being measure is the Speed Adjust Potentiometer.

4.4 LCD

The connection of the LCD is fairly straight forward as shown in Figure 12.

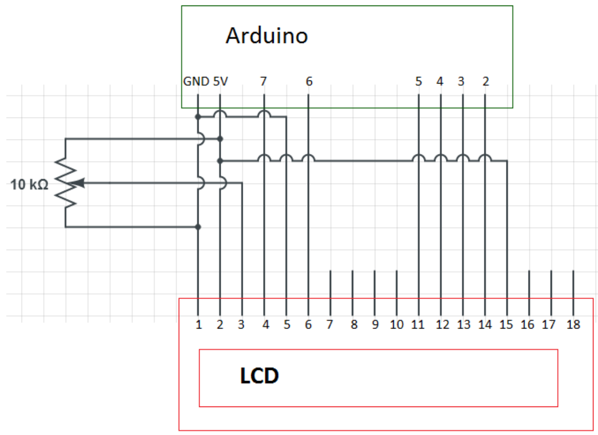


Figure 11. Circuit Diagram for Wiring of LCD

Simple design which can be used for many applications concerning an LCD.

4.5 Software

The code for this part of the program alone is relatively simple. It simply outputs the value for the voltage found in analog input pin 1 which in this case is either the voltage across the potentiometer or the voltage output of the anemometer.

```
int analogPin = 1;
int val = 0;

void setup()
{
        Serial.begin(9600);
}
void loop()
{
        val = analogRead(analogPin);
        Serial.println(val);
        delay(500);
}
```

Figure 12. Program for Testing Motor Speed

A simple program which outputs a number on the scale 0-1023 to represent 0V-5V read through analog pin 1 every .5 seconds.

The Arduino reads voltage between 0V and 5V on a scale of 0 to 1023. This means that the number outputted by the Arduino must be multiplied by 5/1023 if a value in volts is desired. The program for the LCD screen is relatively simple due to the Arduino LCD library.

4.5 Calibration

The circuit above gives a value related to the speed of the motor. This number is relatively steady. It only varies by about 5mV. This device must now be calibrated so that the numbers received by the Arduino are converted to air speed. This was accomplished by taking numerous readings from the Arduino and matching them to the readings of air speed taken with a handheld anemometer. This anemometer was of the windmill variety much like the one shown in Figure 3. The handheld anemometer was taped into place so that all of the readings would be from the same point and with the anemometer in the same position. These data points were all then logged into Kaleidegraph.

Figure 13 shows the full graph of all the data points taken. Having Kaliedagraph create a line of best fit would yield an equation which could be used to calculate the air speed at a given voltage. However, a best fit line of this entire graph would yield a very poor result. It is instead split into five separate sections. Section 0 is simply the section of the graph where all the points are correlated to a speed of 0. Sections 1 through 4 are all shown in Figure 14. As shown, Section 1 has a relatively accurate line. However, as the speed increases the best fit line represents the data less well. This leads to less accurate readings at higher speeds. These line equations are used to convert the voltages into air speeds with reasonable accuracy.

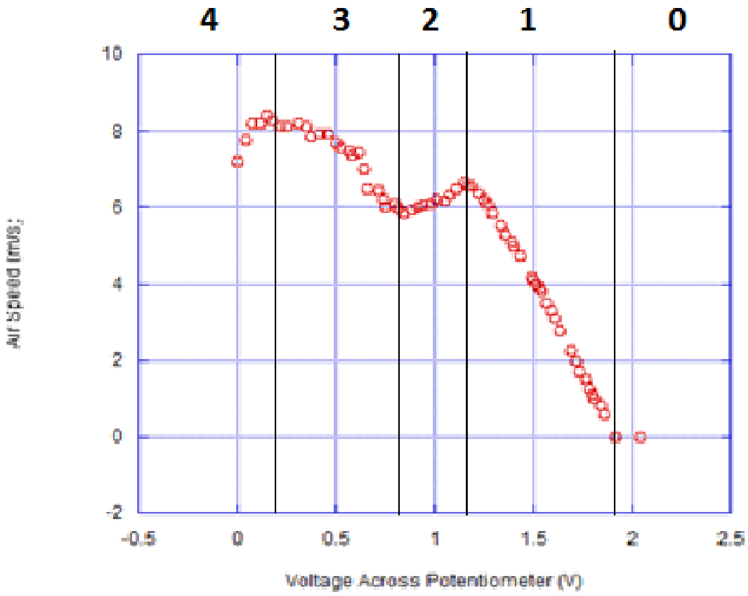


Figure 13. Full Range of Voltage vs. Air Speed Graph

Graph of full range of air speed achieved by wind tunnel. Air speed was measured by a handheld anemometer and voltage is measured by an Arduino microcontroller. The sections are divided by the black lines and are labeled at the top of the graph.

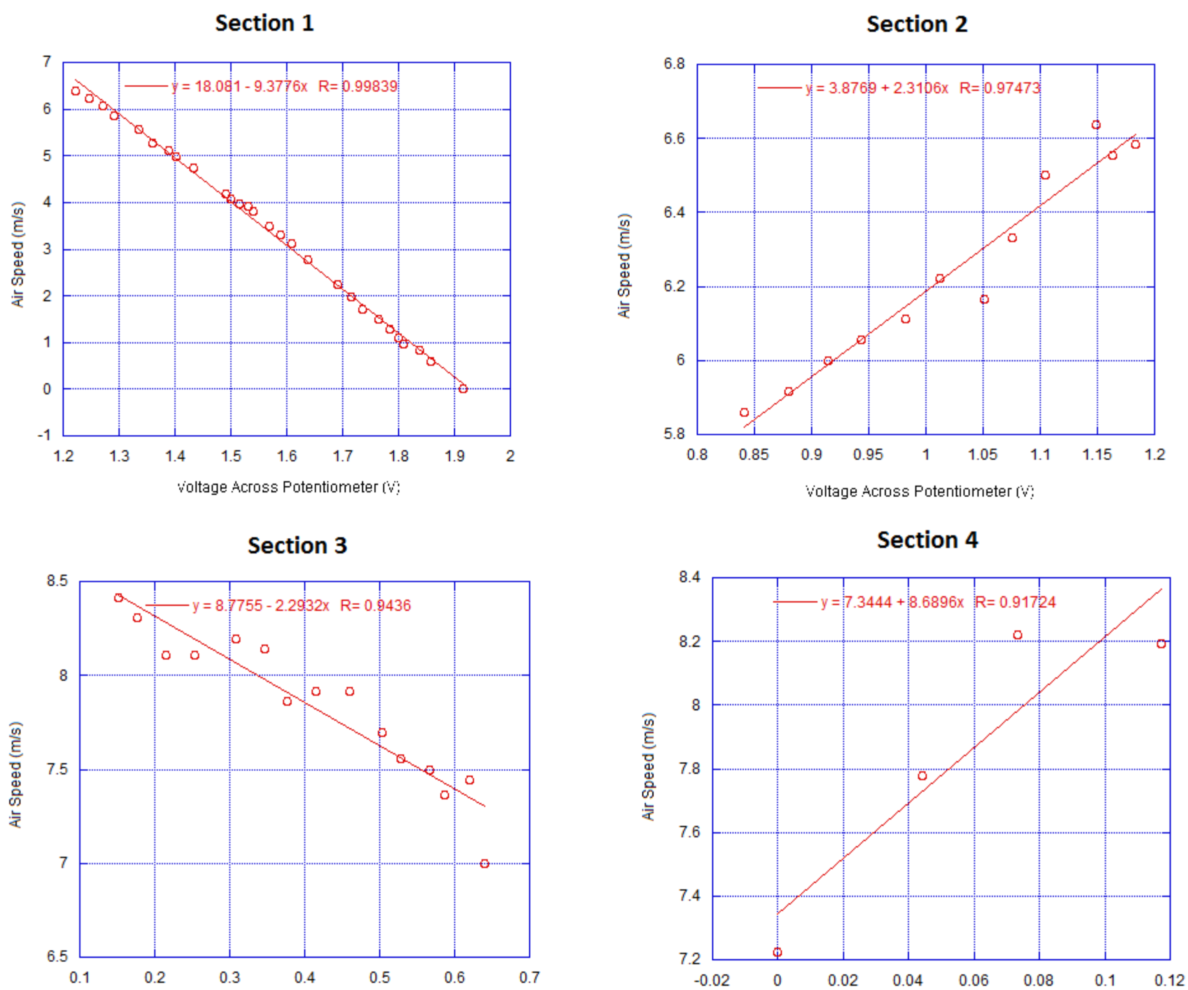


Figure 14. Data Split into 4 Sections with Best Fit Lines

Graph of Figure 13 divided into four sections. Each is fitted to a line of best fit. Section 1 represents the slowest speeds and highest voltages. Section 4 represents the fastest speeds and lowest voltages. The lower speeds are better fit to the line yielding more accurate readings.

5 Results

5.1 Anemometer

The anemometer worked to a limited capacity for a time. The anemometer worked for a range of about 3.1V to 4.3V and from about 0m/s to 5m/s. This means it was able to measure speeds on the lower end of the spectrum of speeds for the wind tunnel. It was also very sensitive on the lower part of the speeds that it was able to measure. It seemed to approach the value of about 4.3V asymptotically. This is why it was not able to measure above about 5m/s.

5.2 Motor Measuring

As was shown in Figure 14, the lower speed measurements were much more accurate than those at higher speeds. The device was able to measure the lower speeds (about 0m/s to 6.5m/s) within about +/- .1m/s. As the wind tunnel gets to higher speeds the accuracy drops considerably to around +/- .7m/s. These are estimations based on the observations made when making the measurements found in Figure 13 and Figure 14.

6 Conclusion

The measurements which were made were not extremely accurate but they may be sufficient for certain applications. This wind tunnel is a homemade device and as such cannot expect to have a completely uniform flow. As a result a measurement that would represent the air speed of the flow through the tunnel as a whole may not be expected to be much more accurate.

There are a few things that could be done to further improve the tunnel. The anemometer needs to be fixed and finely tuned. It may be possible to set up a PIV system. A laser needs to be acquired. PIV software can be found for free on the internet from multiple sources. The department has a high speed camera that could be connected to an Arduino and computer to take images. All that is left is the need to produce seeding particles that can be streamed through the wind tunnel.

7. References

"Anemometer." *Wikipedia*. N.p., 18 Apr 2013. Web. 24 Apr 2013. <http://en.wikipedia.org/wiki/Anemometer>.

"Wind Tunnel." *Wikipedia*. N.p., 13 Mar 2013. Web. 24 Apr 2013. <http://en.wikipedia.org/wiki/Wind_tunnel>.

" Benefits of Acoustic Resonance technology." *fttech.co*. N.p.. Web. 24 Apr 2013. <http://www.fttech.co.uk/technology--benefits/>.

Schotland, R. M. . "THE MEASUREMENT OF WIND VELOCITY BY SONIC MEANS." *Journal of Meteorology*. 12.4 (1955): 386-390. Web. 24 Apr. 2013.

"Flow Sens FS5 Thermal Mass Flow Sensor for all-purpose use in Gases." *farnell.com*. N.p.. Web. 24 Apr 2013. <http://www.farnell.com/datasheets/484569.pdf>.