Wind Tunnel Prospectus

APPC Wind Tunnel

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1 Introduction

A wind tunnel is a chamber that simulates the movement of objects through air to test the aerodynamics of objects in the real world, such as airplanes, spaceships, cars, etc. Flow of air at high speeds generated by a powerful internal fan flow through the tunnel to reflect real life flight conditions. Sensors are usually attached to the test model inside the tunnel to measure parameters such as velocity, temperature, pressure, lift and drag forces, and so on. These sensors provide scientists with data to understand the object-air interaction. Wind tunnels were used by the Wright brothers to test their first successful aircraft, and they are still used extensively today by organizations such as NASA and Boeing.

Wind tunnels are essential for aircraft testing. The same effect of a plane flying through the sky is created with air rapidly moving past a stationary object. All vehicles, whether in air or on ground, require the most efficient and economic design. The cost of testing a thoroughly constructed aircraft is colossal; millions of dollars could be wasted because of a simple mistake. Furthermore, it is difficult to observe the movement of air when the vehicle is in motion. With a wind tunnel, engineers are able to place models of aircrafts inside the tunnel to study the viability and performance of a design. Using a high precision model, engineers control the conditions such as attack angle, wind speed, etc. to obtain accurate force measurements on the model. These careful measurements allow computation of the magnitude of actual forces on the full size vehicle.

There are two types of wind tunnels: closed-circuit and open-circuit. A closed-circuit wind tunnel is a larger and much more expensive wind tunnel. However, engineers obtain the greatest control over airflow with a closed-circuit wind tunnel, producing precise and efficient results. It is constructed in the shape of an oval, where air is recycled and sent around and around the same path, straightened by vanes and honeycomb panels.

The model that is to be constructed for this project is a subsonic, open-circuit wind tunnel. An open-circuit wind tunnel is a long hollow tube with open ends on both sides. It draws air from the outside into the tunnel to the test section, and the air is pushed back out to the other side as exhaust. This design can be made with much less costly materials, and although it does not give complete control of airflow, it is less expensive to build and use. The tunnel is generally operated by engineers in a control room.

The design of a wind tunnel must be carefully planned out to it ensure highest functionality. There are five major sections of an open-circuit wind tunnel. From the beginning to the end, they are the Settling Chamber, the Contraction Section, the Test Section, the Diffuser Section, and the Drive Section.

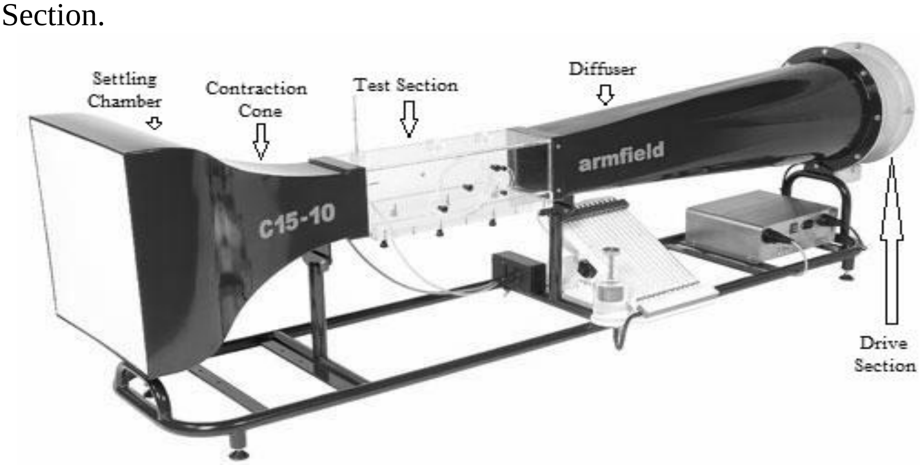


Fig 1. An example open-circuit wind tunnel with all five sections labelled. Starting from the front to the back are the Settling Chamber (or Plenum), the Contraction Section, the Test Section, the Diffuser Section, and lastly the Drive Section.

The Settling Chamber, otherwise called the Plenum, is the front part of the tunnel where the air initially enters through. This is where an airflow straightener, usually in the shape of a honeycomb or mesh screens, is placed to straighten airflow and reduce turbulence. The airflow straightener works to create air that's as uniform as possible in the test section. The settling chamber is the widest part of the tunnel with the greatest cross sectional area.

Following the Settling Chamber is the Contraction Section, where the size of the tunnel decreases dramatically. This forces a large volume of air to travel through a small opening. From the continuity equation for fluid flow which states that,

$$m = \rho_{i1} v_{i1} A_{i1} + \rho_{i2} v_{i2} A_{i2} + .. + \rho_{in} v_{in} A_{im}$$
$$= \rho_{o1} v_{o1} A_{o1} + \rho_{o2} v_{o2} A_{o2} + .. + \rho_{om} v_{om} A_{om} \qquad (1)$$

Where
m = mass flow rate (kgs^{-1})
ρ = density (kgm^{-3})
v = velocity (ms^{-1})
A = area (m^2)

The Mach number is the ratio of speed of aircraft (or any object) to the speed of sound. It is obvious that for this experiment, the wind is subsonic so the Mach number will near 0. Coupling the conservation of momentum and isentropic flow equations, the change in air density for compressible flows is calculated by,

$$-M^2 \frac{dV}{V} = \frac{d\rho}{\rho} \qquad (2)$$

Where
M = Mach number
V = Velocity (ms^{-1})
ρ = Density (kgm^{-3})

Since the Mach number is close to 0, it is seen from the equation that the air density remains nearly constant in the wind tunnel to be constructed. Thus equation (1) can be modified to

$$q = v_{i1} A_{i1} + v_{i2} A_{i2} + .. + v_{in} A_{im}$$
$$= v_{o1} A_{o1} + v_{o2} A_{o2} + .. + v_{om} A_{om} \qquad (3)$$

Where
q = flow rate (m^{3}s-^{1})
Therefore
$\rho_{i1} = \rho_{i2} = ... = \rho_{in} = \rho_{o1} = \rho_{o2} = ... = \rho_{om}$

It is evident that contracting the cross sectional area will greatly increase the velocity of air flowing into the Test Section which follows the Contraction Section. Pressure will also decrease with the increase of velocity.

The Test section is where the model is placed and tested under straightened airflow. This section experiences the highest air velocity and has the smallest cross sectional area out of the entire tunnel. Sensors are placed on the test object in this section to obtain measurable variables. It is usually made of transparent material so that engineers could make observations in real time.

The Diffuser Section then follows. The cross sectional area of this section slowly increases, increasing the volume, smoothly slowing down the air's velocity while causing minimal turbulence to the airflow in test section. This widening / expansion of the section leads the air to the fan.

Finally, the Drive Section is found at the very end of the wind tunnel. This is where the fan is placed, creating high-velocity air flow. The fan is placed at the very back to pull air into the tunnel instead of blowing air in. This reduces incoming air turbulence, allowing for straighter, more uniform air flow in the test section. The fan faces outwards to draw air in, allowing for greater airflow control.

The construction of the tunnel will include all five parts detailed in the explanation above. The ultimate goal is to construct a wind tunnel with a strong enough wind speed to generate lift and drag forces on four different airfoils. These forces must be measured, calculated, and displayed using different sensors, as well as wind velocity. The shape and size of the airfoils and the different sections of the wind tunnel, the sensitivity, function, and size of the sensors, and the size and airflow of the fan to be used are to be carefully taken into account to construct a functional wind tunnel.

2 Wind Tunnel design

2.1 Design

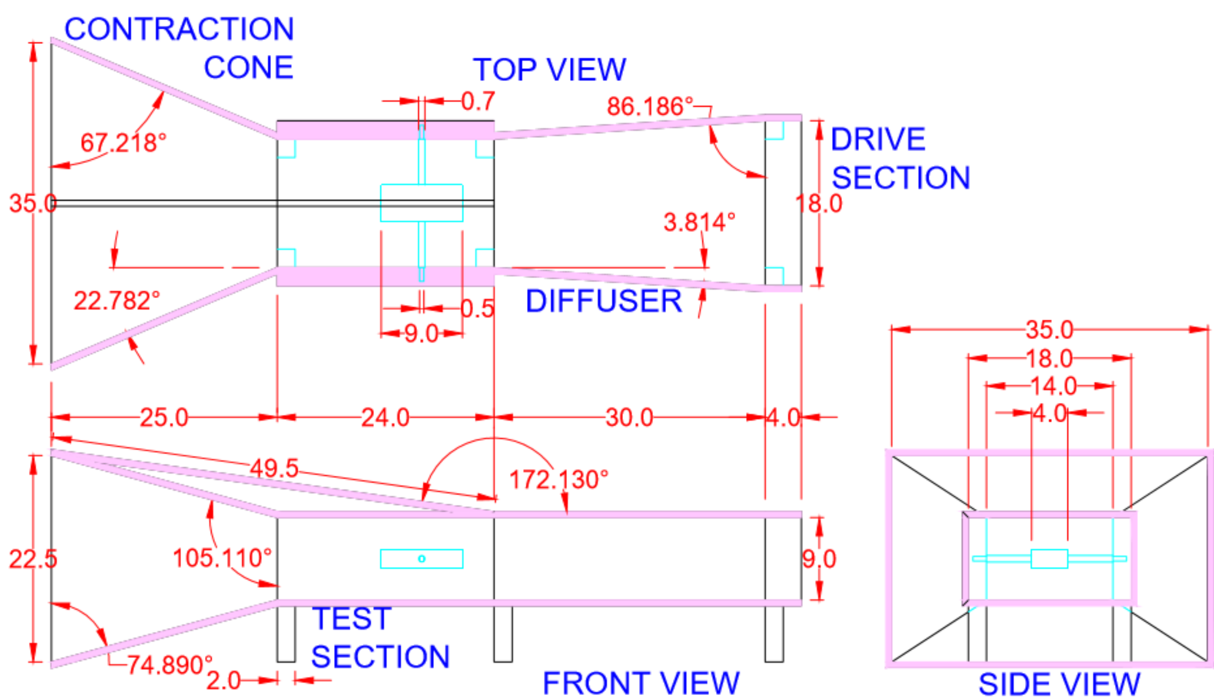


Fig 2. The blueprints for the wind tunnel. The different sections of the wind tunnel are labeled, as well as all relevant measurements. All labeled distances are in cm. Structures designed to support the wind tunnel can be seen in the front view, and the supporting of the foil is outlined in the top and side views.

In order to contain the air flow and collect measurements, a wind tunnel structure must be built. This structure must not only serve as a testing section for the lift and drag forces over various airfoils, but it must also compress the air flow to increase the velocity. However, this is constrained by the size of the fan. As two square fans of 9 cm are used side by side, the maximum width of the testing section is 18 cm, while the maximum height is 9 cm. These fans will be placed at the end of the diffuser, the part of the wind tunnel that allows the wind to slow down before exiting.

The diffuser should be designed so that the exit opening is larger than the test section. Therefore the test section must be smaller than 18 cm by 9 cm. However, compressing the section vertically is not an option as the boundary layer separation effects of the tunnel must be taken into consideration. Thus, there must be more than 2 cm of air space on all sides of the airfoil. Assuming an average airfoil height of 2 cm, it is not feasible to reduce the 9 cm height for the test section, with any real effect. Instead the compression was effected horizontally, decreasing the width from 18 cm to 14 cm. This maintains the 2 cm allowance for edge effects, as the average airfoil width is 6 cm. This also leaves plenty of space for extra sensors when attempting the 3D bonus component.

The next step is to determine the sizing of the contraction cone. There are several factors that affect this process. The main purpose of the contraction cone is reduce both the mean and fluctuating velocity variations to in order to increase the corresponding mean velocity. Boundary layer separation must also be minimized by taking into consideration the adverse pressure effects that come from compressing the air flow. By extending the length of the contraction cone, the pressure effects are delayed and the boundary layer becomes thicker. As a result, the contraction cone length should be relatively small. Another factor that should be taken into consideration is the contraction ratio. The same height and width ratio was maintained for both the contraction cone and the testing section. In addition, a contraction ratio of 5:2 was chosen for the cone.

In order to determine the cone length, research was conducted. It was found that a length to height ratio smaller than 0.67 results in flow detachment at the nozzle between the cone and the test chamber. At the opposite end of the spectrum, a ratio greater than 1.79 produces a very large boundary layer. Because the wind tunnel is not square, the chosen length must fulfill the ratio requirements for both the height (22.5 cm) and the width (35 cm). Therefore, a length of 25 cm is chosen, giving a vertical ratio of 1.1 and a horizontal ratio of 0.71.

In order to access the airfoil, the top of the test section will be attached on hinges from the top. This section will also be constructed out of clear, hard, plastic, so that he airfoil can be seen while testing is happening. This hinge design will have to have an airtight seal and connection when closed. Therefore the outside of this door will be reinforced with rubber casing that will provide an adequate seal when force is applied via the clasp.

The majority of the wind tunnel will be constructed out of plywood, except for the plastic top. In addition, the sides of the test section will be constructed out of 3/4" as opposed to the 1/4" width used on all the other parts. This is because the dowels holding up the airfoils must be inserted into these walls. Refer to the airfoil section for more information.

2.2 Support Mechanisms

As wood is often made available to consumers in thin, flat pieces, this wind tunnel needs to be constructed in components of flat pieces of wood. For this wind tunnel to be operational, the wooden pieces must be held together reliably.

In this wind tunnel, the basic and effective way to hold wood together is through a combination of wood glue and nail. This method will be used for construct the contraction cone, the test section, the diffuser and the drive section individually.

To connect the contraction cone and the test section, a triangular piece of wood that extends from the far end of the contraction cone to the opposite end of the test section is used. This triangle is necessary as it provides the extra support needed to compensate for the drastic increase in size as well as weight. The triangle will be attached to the top center of the contraction cone and the test section using glue and nail.

To connect the feet of the wind tunnel to the test section, diffuser, and drive section, wood glue and screw is used. A screw fastens two separate components much tighter than a nail. The legs are an important component of the wind tunnel it supports all of its weight and holds it parallel to the ground, and hence, such a technique is used. Although screw is more secure than nail, it is harder to implement, more expensive, and only optimal under certain conditions.

Lastly to connect the test section to the diffuser and the diffuser to the drive section, a flat metal connecting bracket will be used. It will be tightened with a screw on the bottom side. As there are no angles to connect the sections using nails or screw, using a metal connecting bracket on one of its flat surface is secure and efficient.

2.3 Airfoils

The cross sectional area of a wing, in this case the wing model to be placed in the test section, is called the airfoil. Usually the airfoil simulates a life-sized airplane wing to test its geometrical viability. Airfoil is a curved structure, generally designed to produce the most lift and the least drag for the design to be usable in real life.

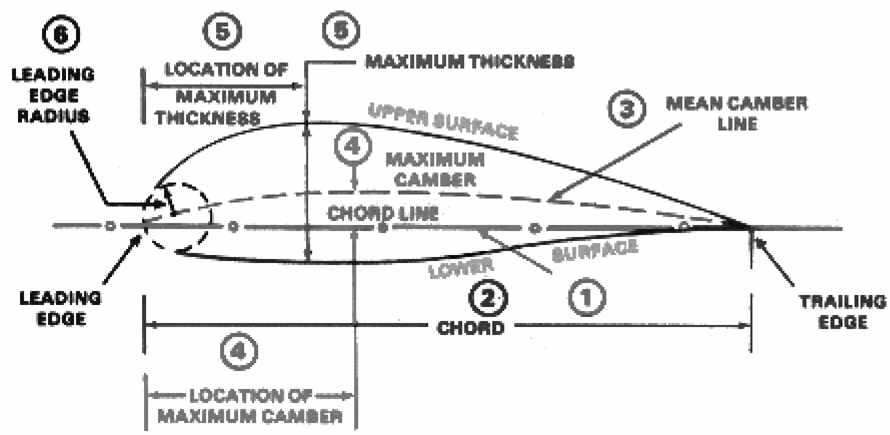


Fig 3. The geometry of the cross sectional area of a wing, or an airfoil. The locations of the leading edge, the trailing edge, the mean camber line, and the chord line are labeled.

The leading edge of an airfoil is found at the bottom of the front of the foil. At the back of the wing, on top of the airfoil is the trailing edge. The chord line is the distance from the leading edge to the trailing edge. Although not depicted in the diagram, the distance from one edge of the wing to the other edge is called the span. The top view of the wing is called the planform. The aspect ratio of a wing measures its length and slenderness, and for a rectangular wing, it is calculated by

$$AR = \frac{s}{c} \qquad (5)$$

Where
s = span (m)
c = chord (m)

For the airfoils used with this wind tunnel, the span will be 8.43 cm long and the chord will be 4.00cm. This gives an aspect ratio of approximately 2.1. A component of drag, called induced drag, depends inversely on the aspect ratio. A high aspect ratio wing will produce a lesser amount of drag, consume less fuel and have higher stability. A lower aspect ratio wing will then produce a greater amount of induced drag, but has higher manoeuvrability.

The chord line divides the wing to an upper and lower section. The mean camber line is a line created from the points that lie equidistant from both the top and bottom surfaces of the airfoil. The maximum distance between the chord and the mean camber line is called the camber. The higher the camber value, the more the curvature. The maximum distance between the upper and lower surface is called the thickness.

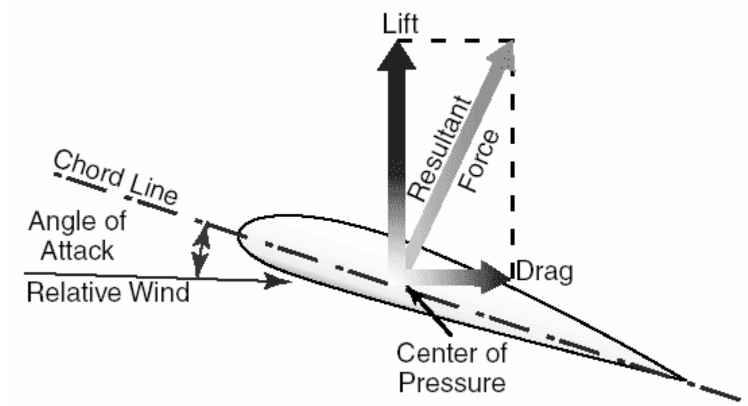


Fig 4. Diagram of an airfoil showing the angle of attack and lift and drag forces. The angle of attack is the angle between the airflow direction and the chord. Lift is the force perpendicular to the direction of airflow, and drag is the force parallel to airflow.

In designing the airfoils, it was decided to keep one section constant, and vary the other. Specifically, the top of each airfoil shape was maintained, while the bottom was changed. The current airfoil designs are shown below.

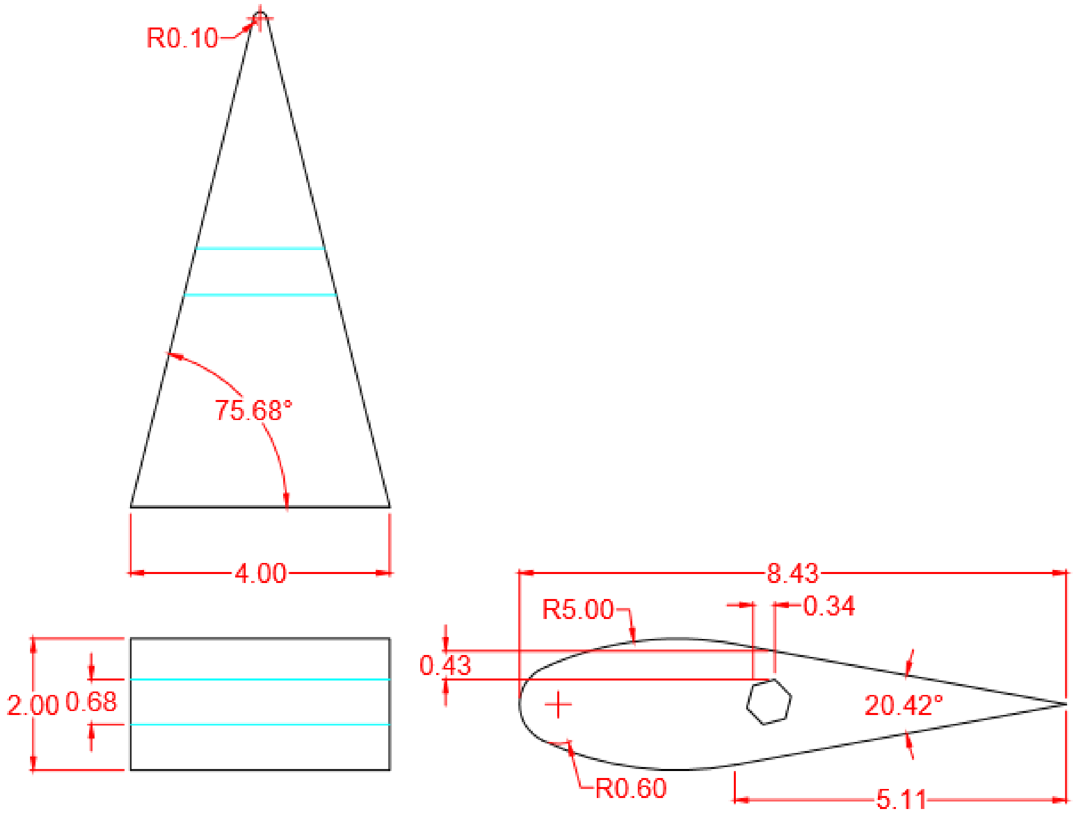


Fig 5. The first airfoil was designed to be symmetrical across the chord line. Therefore the upper camber and the lower camber were the same size. The mean camber line is in line with the chord line. This airfoil also is designed to test our 3D component, as its shape varies in three dimensions, as opposed to two. All labeled distances are in cm.

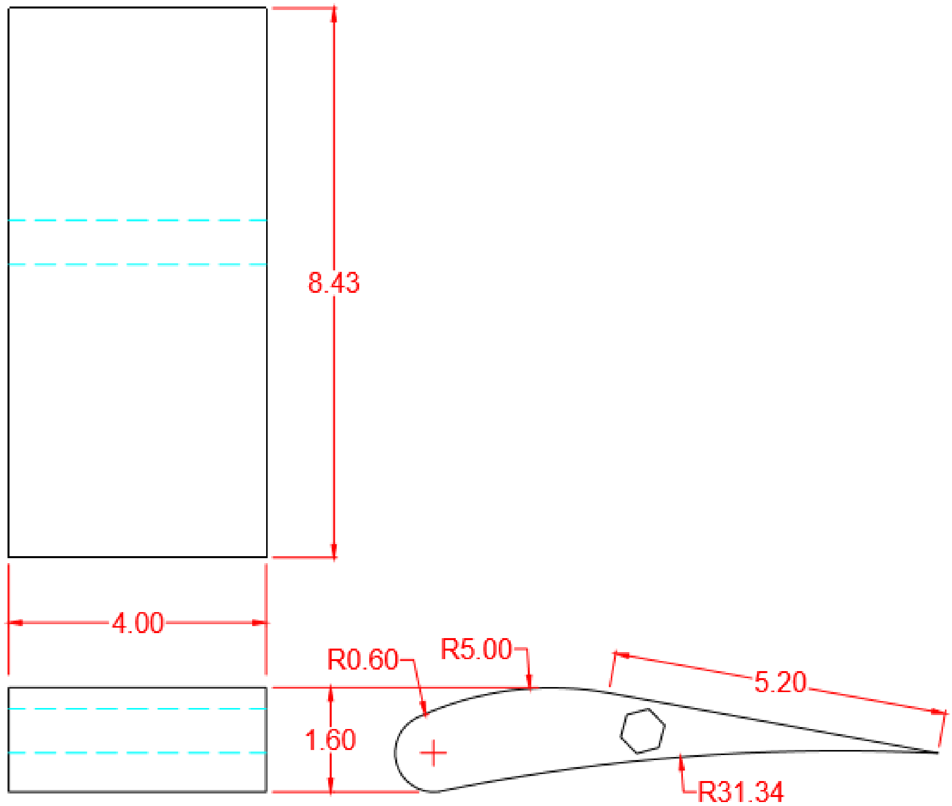


Fig 6. The second airfoil was designed to have a higher lower camber. As a result, the mean camber is much higher than the chord line. Therefore, the airfoil produces high lift and high drag. All labeled distances are in cm.

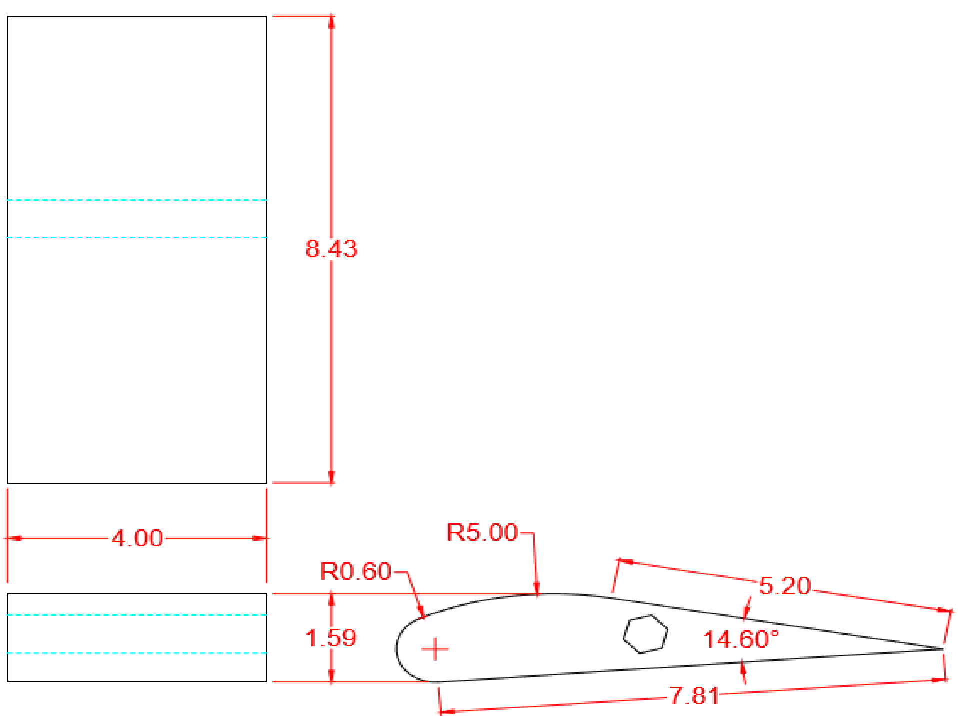


Fig 7. The third airfoil was designed to have a flat bottom. The mean camber line is above the chord line, but not as much as the with the second airfoil. This produces good lift and low drag. All labeled distances are in cm.

The final airfoil shape was designed to be a thin rectangular prism so that all these airfoil shapes could be compared to a base value without any curvature. This will 9 cm x 4 cm x 2 cm.

These four airfoils were chosen to show the effects of different airfoil designs on their aerodynamic forces. All these airfoils will be 3D printed. However, when printing the airfoils, the dimensions will be larger so that they can be sanded to size. This will ensure that the surface is smooth, in addition to shaping the edges correctly, as the 3D printer is not very accurate with sharp edges.

They will be attached to the wind tunnel via dowels that will be inserted into the holes seen in the diagram. There will be one for each side.

2.4 Connection of airfoil to wind tunnel

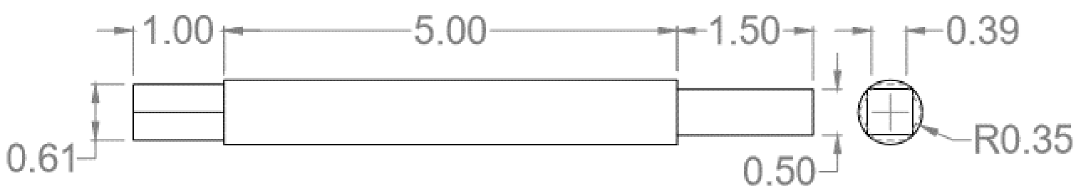


Fig 8. Blueprint of dowel used to connect the airfoil to the wind tunnel. All measurements are in cm.

As indicated on the airfoil diagrams, there is a small hole in the approximate geometric center on each side of the airfoil. That hole is connected to a dowel, which would act as a medium for the sensors, but also as a support for the for the airfoils. On the end of the dowel connecting to the airfoil, the dowel be shaped into a hexagon. This end will be stuck into the airfoil and glued so that it does not rotate inside the hole. This hexagonal shape allows the airfoil to have more variations in its angle of attack, as each side represents a 60° change in the angle of attack.

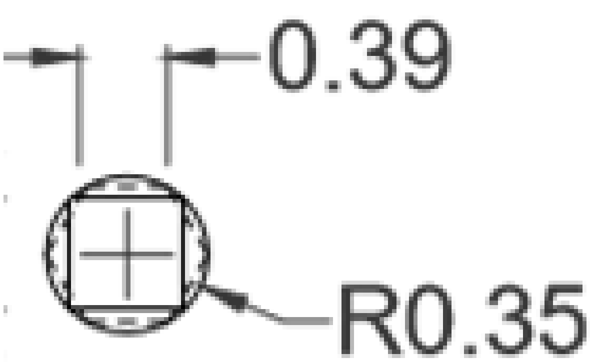


Fig 9. Close up side view of the dowel, depicting the square insert for the wall pit, and the hidden hexagonal insert for the airfoil pit. All measurements in cm.

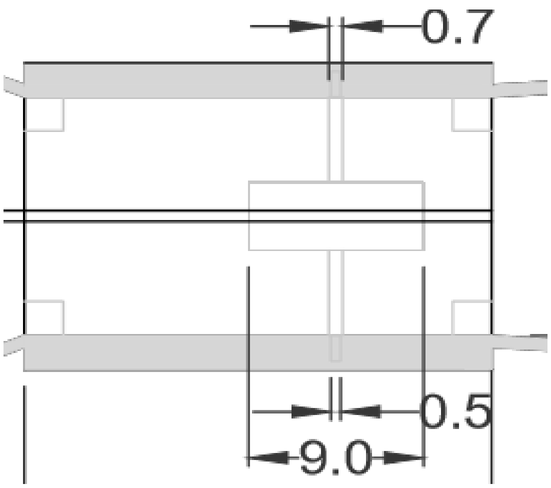


Fig 10. Here, the top view of the test section is shown. The placement of the square section of the dowel inside a pit in the wall can be seen. The sensors will also be placed inside this pit. All labeled measurements are in cm.

The dowel would then extend to the interior wall of the test chamber. The dowel's shape would then translate into that of a cylinder. This symmetrical shape is optimal as it is sturdy, minimizes material used, and also minimizes drag.

On the opposite end of the dowel, the thin cylinder will be translated into a square prism. This prism will fit into a small pit in the interior of the wind tunnel side wall. It will be tight enough so that movements inside are minimized, but not so tight that the sensors would be experiencing undue pressure. All sides of the cube as well as the pit would be sanded to minimize friction, although there would be little space for movement in the pit.

Another benefit of the dowel being connected to a square prism is that it removes the need for another support. If it wasn't for the square end, the circular dowel would rotate in the pit, allowing the airfoil to spin ridiculously. Of course there is the option of gluing or tightening the pit so that the dowel would not be allowed to spin. However, this would hinder and obstruct measurements of the aerodynamic forces. As a square has an increased radius at its vertices, it will not rotate in the pit given the dimensional restraints. This reduces the need for additional supports, which may require additional sensors as the drag force may be spread out onto them. Like the square, the hexagonal prism on the other end also shares the same benefit.

In order to construct this mechanism, first a square pit that is 1.5 cm long will be made in the thicker walls that make up the side of the test section. This pit will be 0.5 cm in height and width, and located in the geometric centre of each wall.

The next problem to address is the difficulty of placing the airfoil samples inside the testing section of the wind tunnel. However this problem is addressed by allowing one of the pits to open via a small door to the outside. As the airfoils are not attached to the dowels directly, but instead are inserted into square slots on the side of each wing, they can be secured between the two dowels. When the door is opened, the dowel can slide out and the wing can be placed between them. This is kept in place when the door is closed.

2.5 Wind source

A strong and viable wind source is the backbone of any wind tunnel, and hence many aspects of the wind source were taken into account. Dimension, power supply, wind speed control, propeller shape, motor, placement, and etc. were all topics of discussion.

However there exists some basic constraints to the design of the wind source. Firstly, the wind source can be only powered by the following accessible power supplies. The Arduino board, which is connected to the sensors as well as the 7-segment display, can be used to power the fan, as well as control wind speed using merely software. However, the Arduino board is capable of only 3.3V or 5V. Another power supply is the ATX12V, which is used to power the typical desktop computer. It converts AC current from a wall socket to a variable DC current between +12V to -12V. This is capable of producing 10A of current. Lastly, the fan can be attached to an Arduino board, but also powered using an additional battery.

Another constraint to the design is cost. In the prototyping and the construction of the wind tunnel, there are costs which are non-negotiable. For example, sensors, resistors and wires, control board, and of course, the construction materials. These components and all others all add up and hence to an approximation, the wind source is allocated to a $40 maximum. As such, the wind source must be efficient and effective, both in terms of its systematic capabilities as well as economically.

However, the most fundamental design constraint revolves around the power of the fan. As the purpose of this undertaking is to construct a wind tunnel which will output values of forces on an airfoil, the sensors must be able to detect a force. The strain gauges will not be able to detect a resistance if the wind is miniscule. These constraints are the basic guidelines to the wind source design: Create a wind source that will run on any of the previously determined power supplies options, that will generate wind fast enough for forces to be detected, all the while keeping cost under $40.

There were two basic possibilities regarding the structure of the fan. The first was using computer fans. Although seemingly weak, computer fans are extremely versatile as they come in all different forms and with different powers. They have the added advantage of having the motor and the blade in a single unit. The other option was taking a pre-existing fan blade or designing a new fan blade, and powering it using a dc motor.

A primary consideration of the two options suggested that the latter was the better candidate. Firstly, both a new fan blade and a dc motor are relatively cheap, as an approximation on the price of this setup based on current Canadian fair market value is around $20. This includes the cost of taking apart a 200mm by 200mm fan (one of relatively low cost due to a low motor rotation per minute, which is abbreviated by rpm), and a purchases of a dc motor, which at 9 volts and has a rpm of 7600. This in theory is extremely effective. An industrial level designed fan paired with a motor that has a rpm of around seven thousand times that of a computer fan, it should be clear this is what the wind source should be.

However, this option cannot be effectively implemented, as the power supply cannot support this method. In order to reach the potential required for this fan while allowing the fan speed to be changed, the only method that can be used is by attaching the Arduino board with an additional battery source. However, this method does not provide nearly enough amperage to make the motor run fast enough. The current coming out of the Arduino is in the range of milliAmperes, and nowhere near large enough to power the dc motor. Even with the addition of an additional battery, the current needed for the fan to spin at a faster speed than a higher-end computer fan cannot be viably built given the predetermined constraints. Through a consideration of the initial concept, it was discovered that the optimal power supply for the wind source was an ATx12V, as the max current for this power supply goes up to 10A, which is optimal for a high performing fan.

Like many aspects of the wind tunnel design, there are many considerations to be made in terms of computer fan design. For one, it needs to be spinning at an extremely high rate, moving enough air for the force sensors to detect. In terms of how powerful a fan is, values of cubic feet per minute (CFM) were compared, of course all the while taking budget into account. CFM is the measurement of velocity at which air flows in and out of a space. CFM is a far more important factor to consider, when compared to other specifications such as rotation per minute (RPM), or even fan dimensions. CFM, as previously defined, determines how much air is flowing through the wind tunnel, and at exactly what rate. While RPM calculations are significant, they do not determine how much air is going through, which is also dependent on the fan's characteristics. These characteristics include the shape of the blades, which come in different curvatures, and dimensions, and designs of the fan poses are a significant factor in how much force the wind supply generates, and all these factors are taken into account by the CFM number.

To calculate force generated, CFM can be converted into MKS units, cubic meter per second (CMS).

Let x be an arbitrary constant for CFM.

Converting to CMS,

$$x\ \frac{ft^3}{min} = x\ (0.0283168)\frac{m^3}{min}\frac{min}{60s}$$

$$x\ \frac{ft^3}{min} = x\ (4.719E-4)m^3s^{-1}$$

Another approximation made for test tube dimension (not taking length into consideration) is 150mm by 150mm.

$$A_{Cross\ Section} = ((150mm)(\frac{1m}{1000mm}))^2$$

$$A_{Cross\ Section} = 0.0225\ m^2$$

To find air velocity,

$$v = x\frac{(4.719E-4)}{0.0225}\frac{m^3}{sm^2}$$

$$v = x(0.0209763)\ ms^{-1}$$

Let's use lift to further this approximation. Lift is defined as the force perpendicular to the wind flow. In other words, lift in the wind tunnel is the net forces about the y-axis. However, to find lift without calculating net force, the lift equation can be used.

$$L = \frac{1}{2}C_L\rho v^2 A \qquad (4)$$

Where

C_L = coefficient of lift
ρ = air density
v^2 = velocity
A = wing area

Taking air density at 20 ℃ and 101.325 kPa, dry air has a density of 1.2041 kgm^{-3}, and taking an arbitrary coefficient of lift of 1 (for ease of calculation as well as for a medium representation for typical lift coefficient). Another approximation is made for wing area, with dimensions of 60mm by 80mm. This gives a surface area of 4.8E-3 m^2.

$$L = \frac{1}{2} C_L \rho v^2 A$$

$$L = \frac{1}{2}(1)(101.325)(0.0209763x)(.06)(4.8E-3)$$

$$L = x\,(0.0030606)N$$

For a lift of one Newton, a CFM of over 300 is needed. However, this level of lift can be reached with a CFM under 300. Firstly, the angle of attack is a major factor. By increasing the angle of attack, forces of lift can be further amplified. However for this sensor setup, this will not amplify the force detected. The air flow can be increased by reducing the cross section of the test area. As the air transitions from an area of high volume and low pressure, into an area of low volume and higher pressure, the velocity will be increased, and therefore increasing the force generated.

To ensure the strain gauge sensor will detect a reasonable amount of force (along with reasonable digits of uncertainty), the velocity of the fan must be maximized. There are many arrangements to optimize this problem. Find a fan with a high CFM, find a fan that is large in dimension, use multiple fan, or a combination of the above. The fan will be placed at the back of the wind tunnel, as then it will draw air into the wind tunnel by blowing air out of it. Drawing air into the wind tunnel minimizes turbulence, as the wind is pulled from a long, narrow container. This way, there is no deviation in pressure, airflow, or composition of the air being pushed through the wind tunnel.

In the case of setting up multiple fans, the fans can be only set up side by side. While many computer systems feature a fan on both end, sucking air in and blowing air out, this is not optimal for this undertaking. Although this is great for airflow control and maintaining wind speed over a distance, the wind speed will not change, and the price and circuit complication will be doubled. The fan also cannot be placed on top of each other. This method will not amplify the airflow at all. In fact, it will decrease the airflow to less than that of just a single fan. The fan blowing into the second will actually act as turbulence, nullifying its effectiveness. Setting the fans side by side will increase the CFM as there will be two or more identical fans blowing over an area twice, trice or quadruple of one fan. The airflow will not be an exact multiple of the number of fans, as the air will be drawn in from air sources extremely close with each other, resulting in potential turbulence. Nevertheless, the airflow will still increase quite dramatically.

Stacking two computer fans with mediocre CFM and typical case dimensions side by side is the most optimal method. Modern day computer fans are often a compromise of noise reduction technology and airflow. As such, finding a computer fan with high CFM and high noise for a cheap price is quite simple. The computer fan chosen for this undertaking is a Nidec Beta V TA350DC, model M34789-35. It is a 12V DC fan with amperage of 1.0A. It is a 92mm square fan, 3.75 cm thick, which has a maximum CFM of 110. Having the two fans side by side and compressing the air into the dimension of one will produce adequate force for the strain gauges to detect, as it was even able to detect the force of one blowing on it in an open space. Moreover, this fan features a four pin connection. This means there will not only be two wires for power (one voltage and one ground), but as well as a wire for speed sensor (which will not be used as the fan will not be connected to the motherboard) and a Pulse Width Modulation (PWM). The PWM is a high efficiency speed control that changes the current through the fan by grounding the PWM wire. This gives the wind tunnel far more scientific versatility.

To control the airflow, a potentiometer is used to control the current flowing through the PWM wire. The technical setup will be further elaborated on in *Wiring*. Each fan is controlled by a separate potentiometer, but both potentiometers will be connected through a mechanical gear design (Figure 20), assuring asymmetrical fan speed.

As previously discussed, one method of controlling airflow utilized in this design is the placement of the fans in the back of the wind tunnel, pulling air in as opposed to pushing it. Another method to straighten the airflow is by using a flow straightener. In this undertaking, large straws often used for the consumption of bubble tea, will be held together using x glue, to act as the flow straightener. The straws will be cut to equal size and placed in the frame where the air begins to flow into the wind tunnel. This device will seek to reduce swirl and turbulence level of the airflow, and this method of implementation has been thoroughly researched by facilities such as MIT.

In summary, two computer fans will be set up side by side, and the air entering the wind tunnel will be compressed into a smaller cross-sectional area. The fans will be pulling air in, as they will be placed at the back of the wind tunnel. Airflow will be further controlled as a flow straightener will be constructed and placed on the opposite end of the wind supply. The fan speeds will be controlled by two conjoined potentiometer, changing the resistance as the PWM wire is grounded.

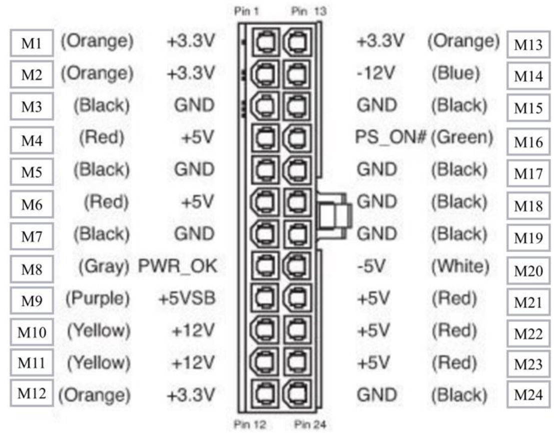
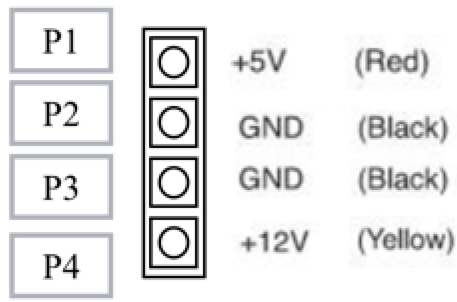
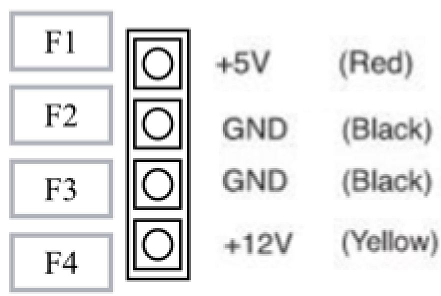
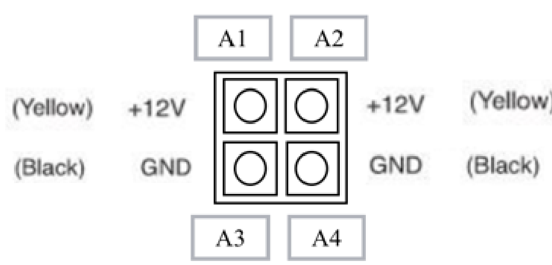
3 Wiring

3.1 Power Source

The source of power for the wind tunnel fans, display, and circuits will be the ATX12V. It is a power supply originally designed to power a CPU, and so has many different bundles of wires. This is ideal because it eliminates the need for multiple power sources, as it is not as practical to operate a wind tunnel that needs to be plugged into multiple wall sockets for power.

The wires come organized in connectors designed for connection to , which is undesirable for securing them to components such as the fan. As such, the connectors will need to be removed. The wires will be cut just below the connector and then stripped in preparation for soldering.

Connector Name	Connector Picture	Wire Identification

Main Connector		
Peripheral Connector		
Floppy Connector		
ATX12V Connector		

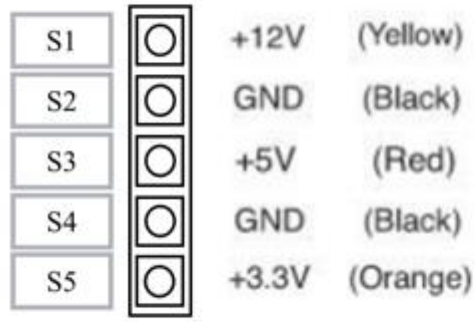
SATA Connector		

Fig 11. Each connector that the power source has contains wires that provide different voltages. These can be recognized by colour, and have been labeled in the chart above. Each wire has also been given a code (a letter + a number) which is labeled in gray boxes. The codes will be referred to in later sections when explaining wiring.

As seen in Fig. 2, the wire M8 is called PWR_OK. It serves as a sort of on/off switch, as the ATX12V will only supply power if this wire is grounded.

3.2 Wiring Diagrams

Each strain gauge needs to be connected to the Arduino, which is used to both provide power to the sensor and receive the output voltage, which can be used to calculate strain. The strain gauges used come pre-wired to a board which amplifies the output, which simplifies the wiring significantly.

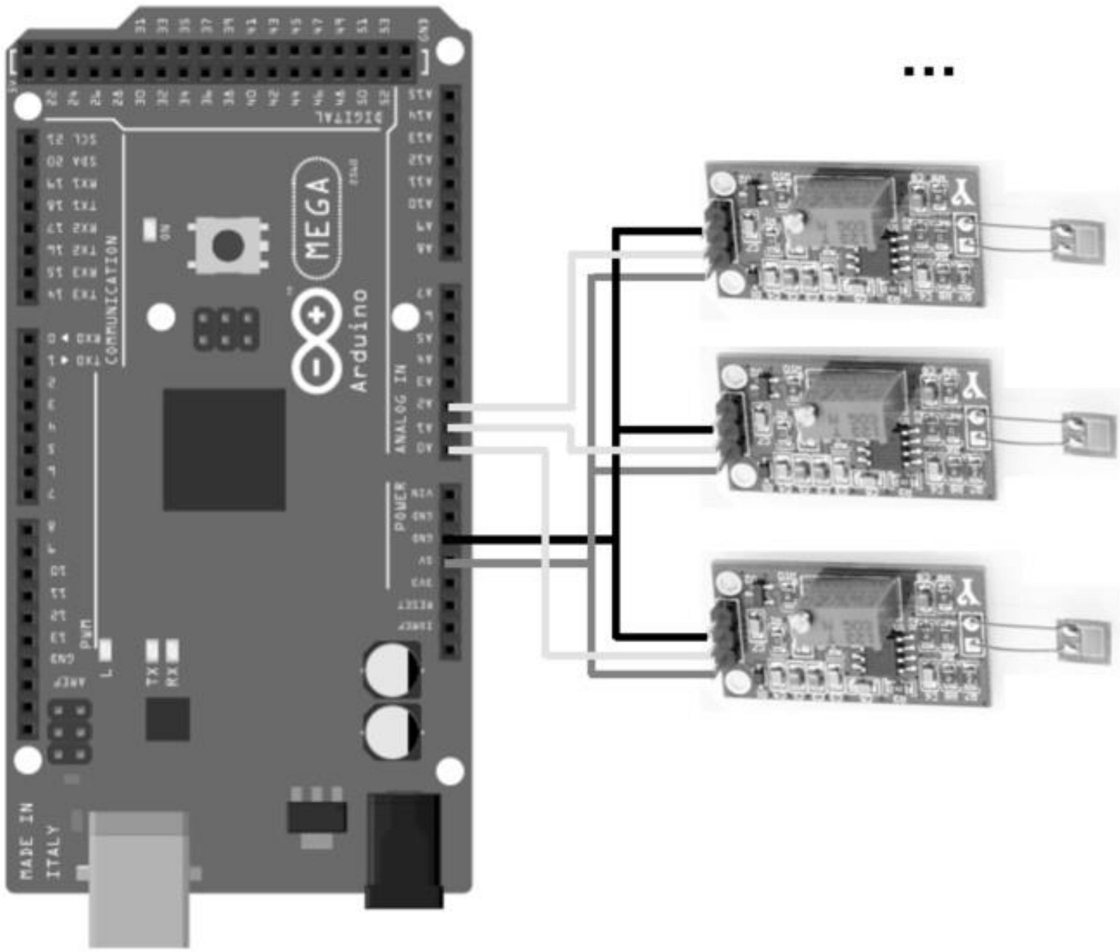


Fig 12. The circuit required to set up the sensors. The pins on the strain gauges are labeled as VCC, OUTPUT and GND. The VCC for each circuit needs to be connected to the 5v pin on the Arduino. The GND pins are to be connected to the GND pins on the Arduino. and each OUTPUT pin on the sensors is to be connected to an Analog Input pin on the Arduino. This circuit can be expanded to include up to 15 strain gauges, with the output pin of each sensor connected to a different input pin (A1, A2, A3, … , A15.)

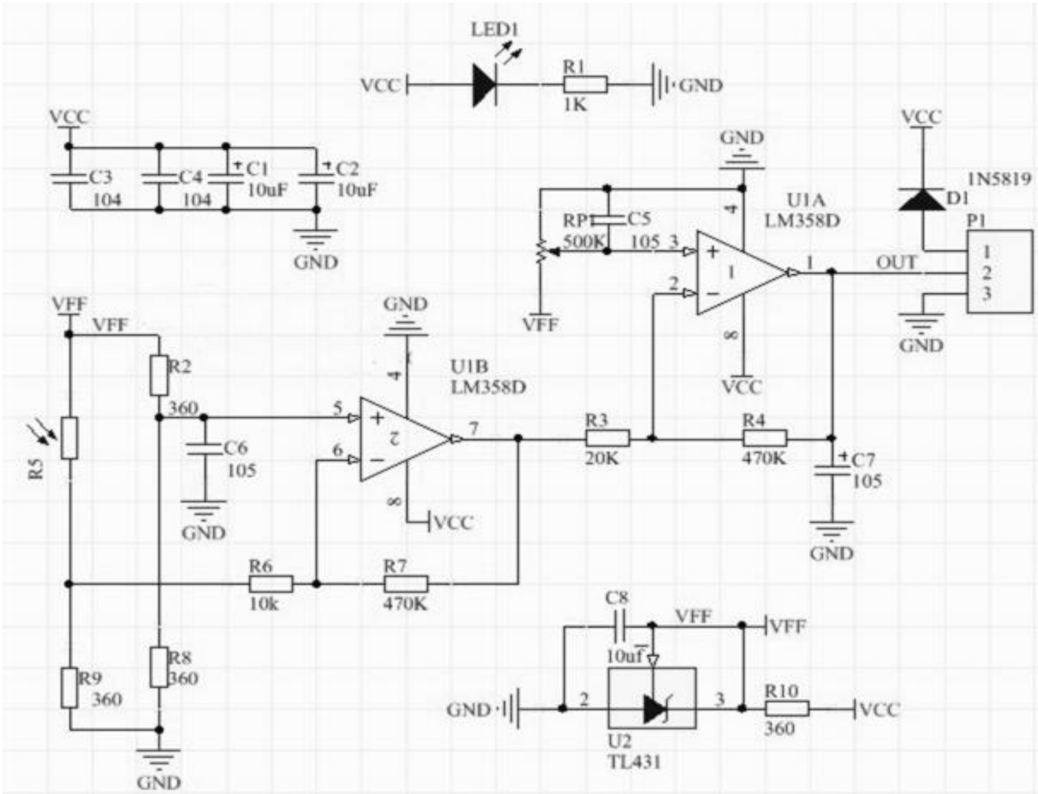


Fig 13. The strain gauge's change in resistance from an applied strain is extremely minimal. Therefore, each purchased strain gauge includes a supplied chip that automatically amplifies the signals according to manual adjustments of the onboard potentiometer. This is the circuit diagram of the amplifying chip.

The measured wind speed inside the wind tunnel is to be displayed using three 7 -segment LED displays. These components will be controlled using the Arduino. The wiring circuit includes the use of a 7447 chip, which reduces the number of output pins of the Arduino needed to operate each digit.

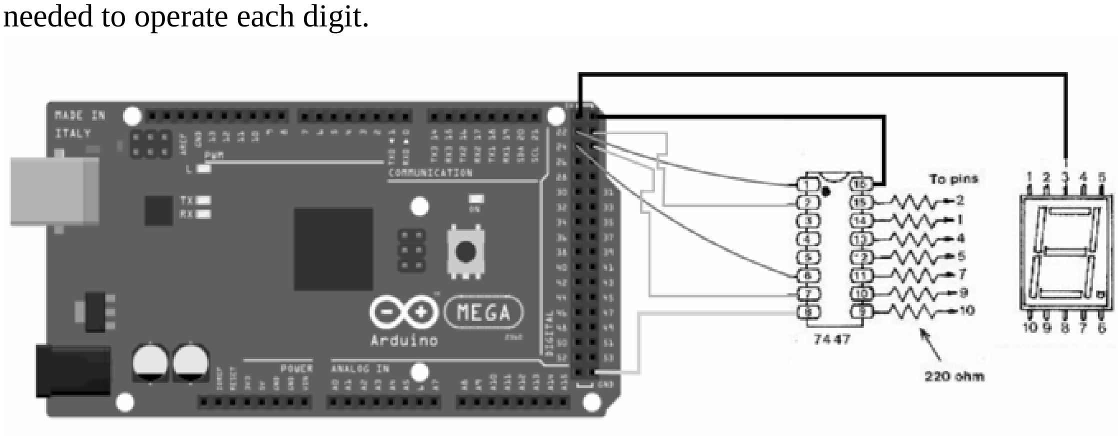


Fig 14. The wiring diagram for connecting a 7-segment display to a 7447 chip to the Arduino board. Both the display and the chip are powered by the 5v pin on the Arduino. A resistance of 220 Ω will be wired in series to each of the LED segments, as shown. In this circuit, the digital input pins 22-25 of the Arduino are used. This circuit will need to be expanded to include three other digit displays. These will be wired in the same way, except they will use the digital input pins 26-29, 20-23, and 24-27.

Another sensor that must be included is the temperature sensor. This wiring is relatively easy, as it consists of three wires; power, ground, and analog output. The temperature sensor operates on 5V, so it can be powered from the Arduino board.

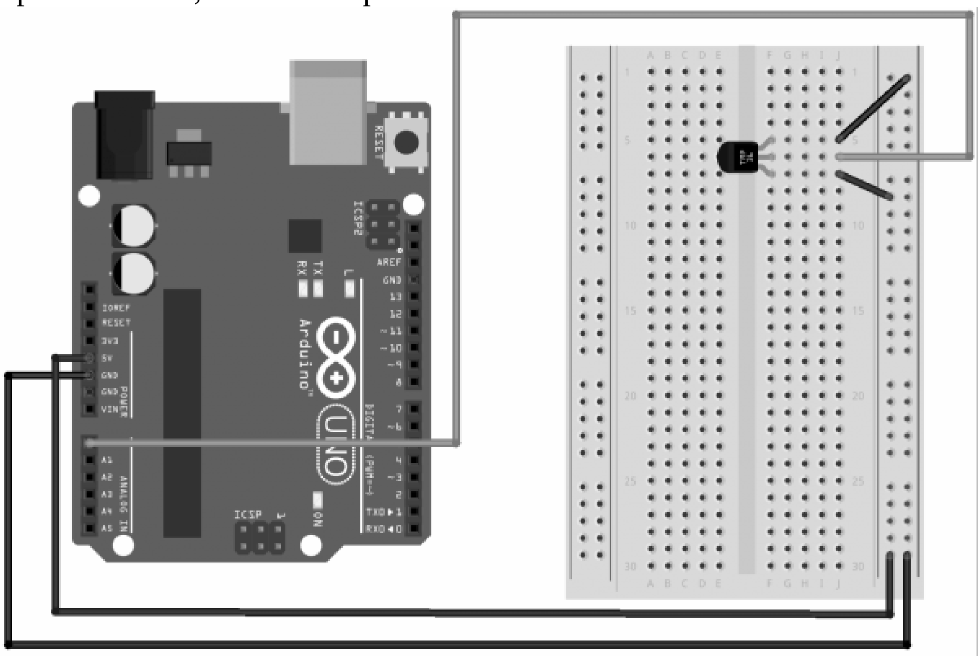


Fig 15. Wiring diagram for the temperature sensor to connect the Arduino board.

Finally, the MPXV7002DP Pressure sensor is wired to +5V, ground, and analog output on the Arduino board. This sensor consists of many pins, but only three are required in this circuit.

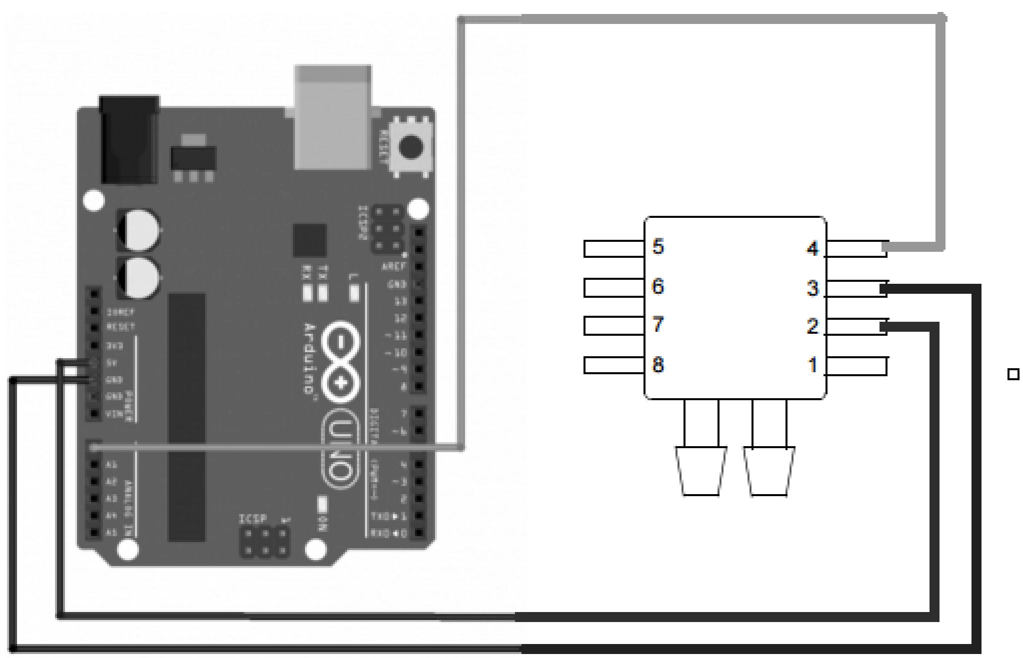


Fig 16. Wiring diagram for the MPXV7002DP Pressure Sensor to the Arduino board

3.3 Potentiometer and Variable Fan Setup

The four wired fans we are using are variable speed fans. They have 4 different coloured wires: yellow, black, blue, and red. The yellow wire is for tachometer output, and is not needed. The red wire should be plugged into a +12v power supply, and the black should be plugged into ground. The blue wire is the control. The speed of the fan is at a minimum when this wire is grounded (with minimum resistance), and at a maximum when it is not plugged into anything (maximum resistance.) The speeds in between can be achieved by using a potentiometer to vary the resistance leading to ground, thus limiting the current that flows through this wire.

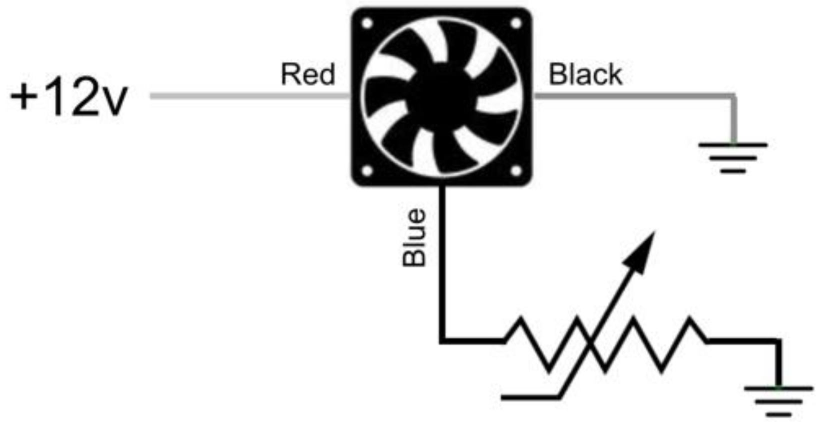


Fig 17. A diagram of the basic circuit that would allow for a variable speed fan to be operated. The resistance range of the potentiometer would have to be chosen based on experimentation done to determine the range of speeds desirable, since the internal resistance of the fan is not known initially.

The specific fan that is going to be used in the wind tunnel is the Nidec Beta V TA350DC Model M34789-35.

Component	Photo of Component	Wire Identification

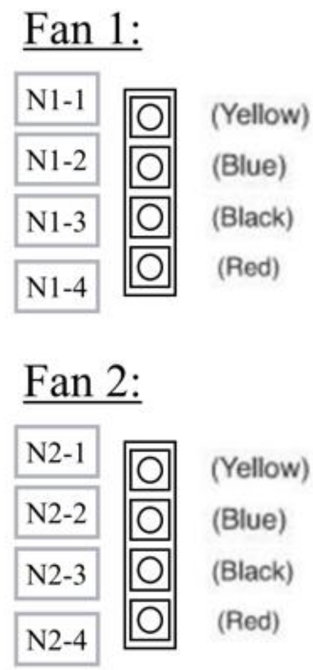
Nidec Beta V TA350DC Model M34789-35		

Fig 18. A picture of the fan being used, along with the specification of the wires used to control it. The wires on the fans can be recognized by colour, and have been labeled in the chart above. Each wire has also been given a code (a letter + numbers) which is labeled in gray boxes. The codes will be referred to when explaining wiring.

In order to use the control wires of the fans to vary the speed of the fans, a circuit was constructed which uses potentiometers to vary the resistance in the wire leading to ground. The speeds of the fans did not need to vary all the way from minimum to maximum because the low speeds would provide enough airflow for the forces on the foils to be detectable. Since higher fan speeds are achieved by having a large resistance, it was decided that using a large resistor connected in series to a potentiometer with a relatively small range of resistances would be the best way to allow for speed control.

An on/off switch was also created using a button switch located on the same board as the potentiometer controls. This switch controls the power supply providing the power to the fan and the control circuit.

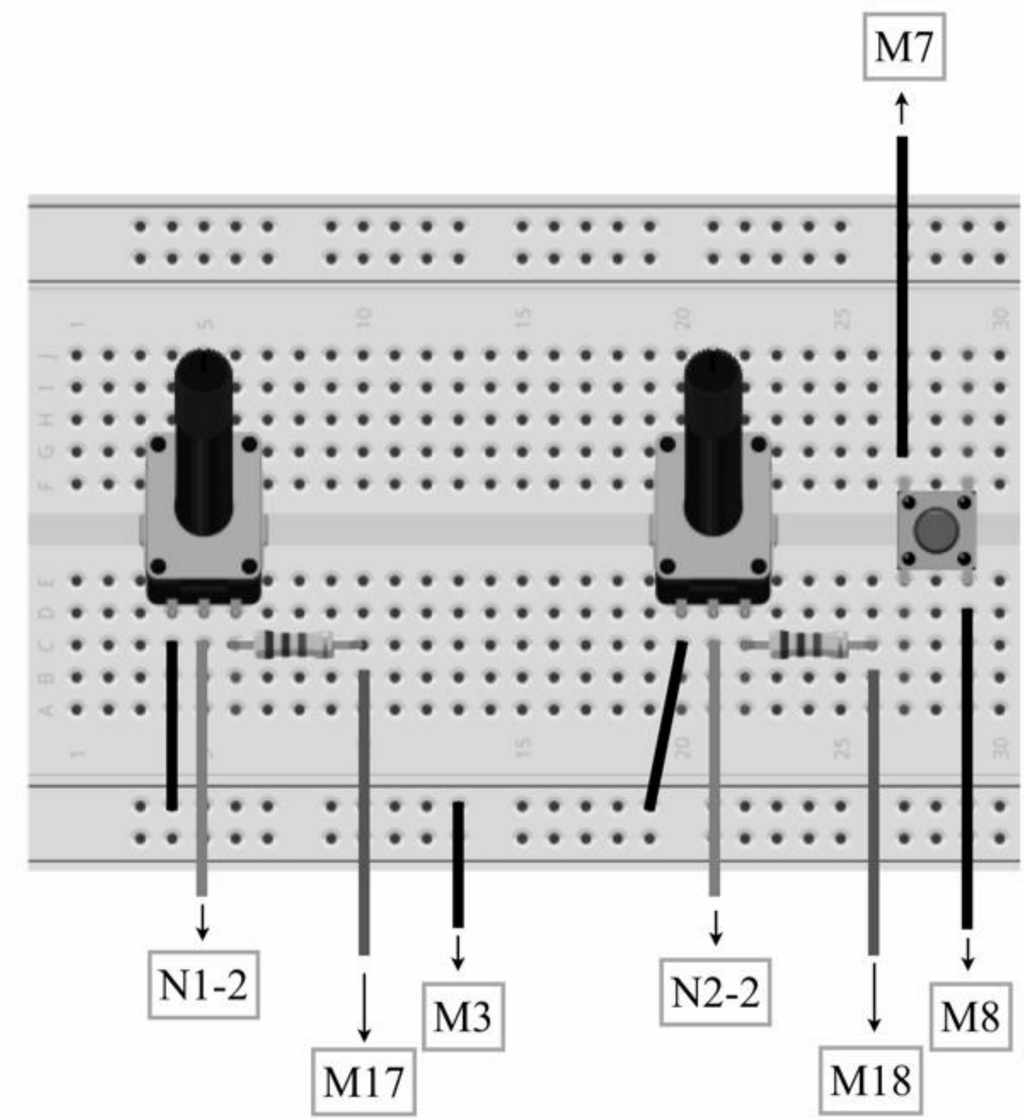
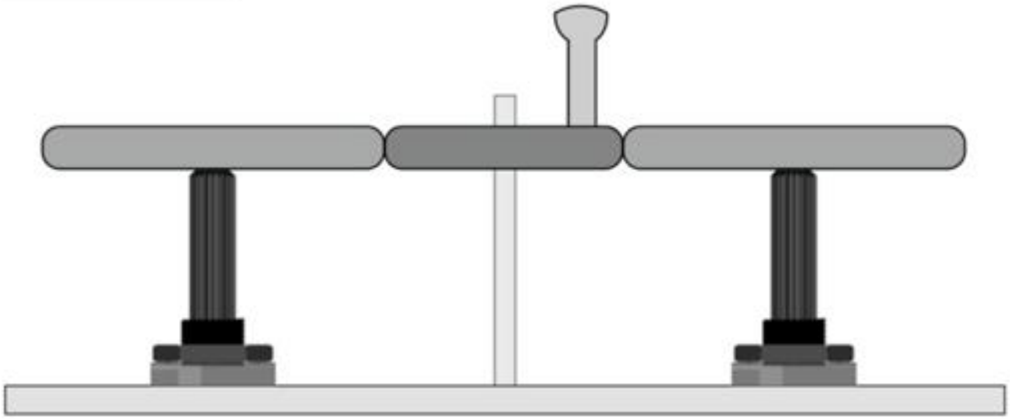


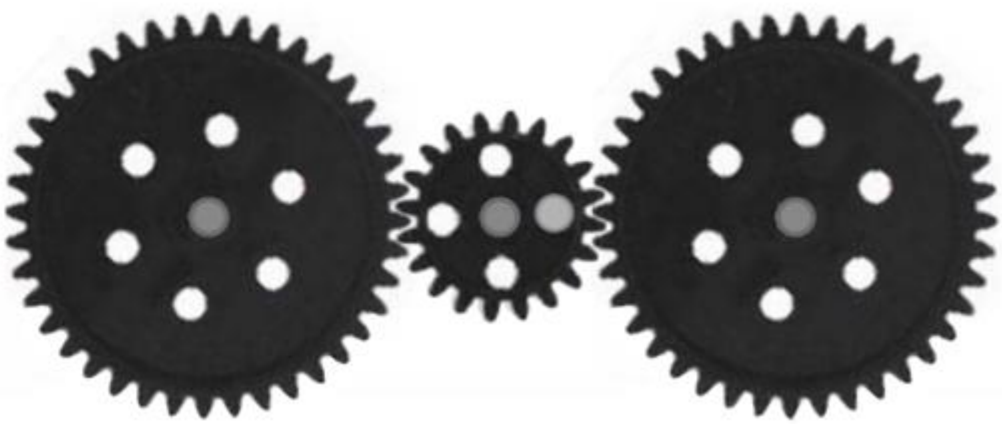
Fig 19. A wiring diagram of the circuit used to allow for variable fan speed. The on/off switch uses a feature of the power supply which requires wire M8 to be grounded in order for the power supply to output any voltage. This circuit connects the control wire from each fan (N1-2 and N2-2) to a potentiometer and a resistor, before leading to ground. The leftmost pin of the potentiometers are grounded. Both resistors are 10M Ω resistors, rated for 1W. The potentiometers are 1K potentiometers, with the same requirement for wattage ratings.

An external mechanical method will be used to synchronize the turning of the potentiometer knobs. A system of gears will be used. By using the properties of gears with different number of teeth, this allows for the potentiometers to be turned more gradually, allowing for more precise changes in fan speed. The physical turning of the knobs will be facilitated by adding a handle onto the center gear, which is supported by a rod fastened onto the board.

Side View



Top View



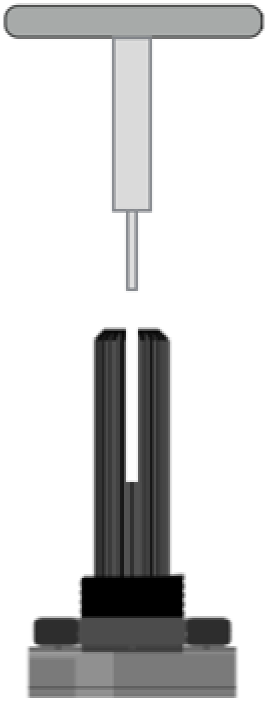


Fig 20. A diagram of the gear system which will be used to turn the knobs of the potentiometers. As seen in the diagram at the bottom, two 40 teeth gear will be secured to the top of the potentiometer knobs using dowels with one end carved so as to fit into the slits on the knobs. A gear with 20 teeth will connect the two. The difference in gear number means that the larger gears will experience fewer rotations per minute than the one in the centre, and so the knobs of the potentiometers will be turned more gradually.

Each fan also needs to be connected to 12V and ground. The wires of the fan should be soldered to the wires of the power supply as outlined in the diagram below. Electrical tape will also be needed to secure the connections.

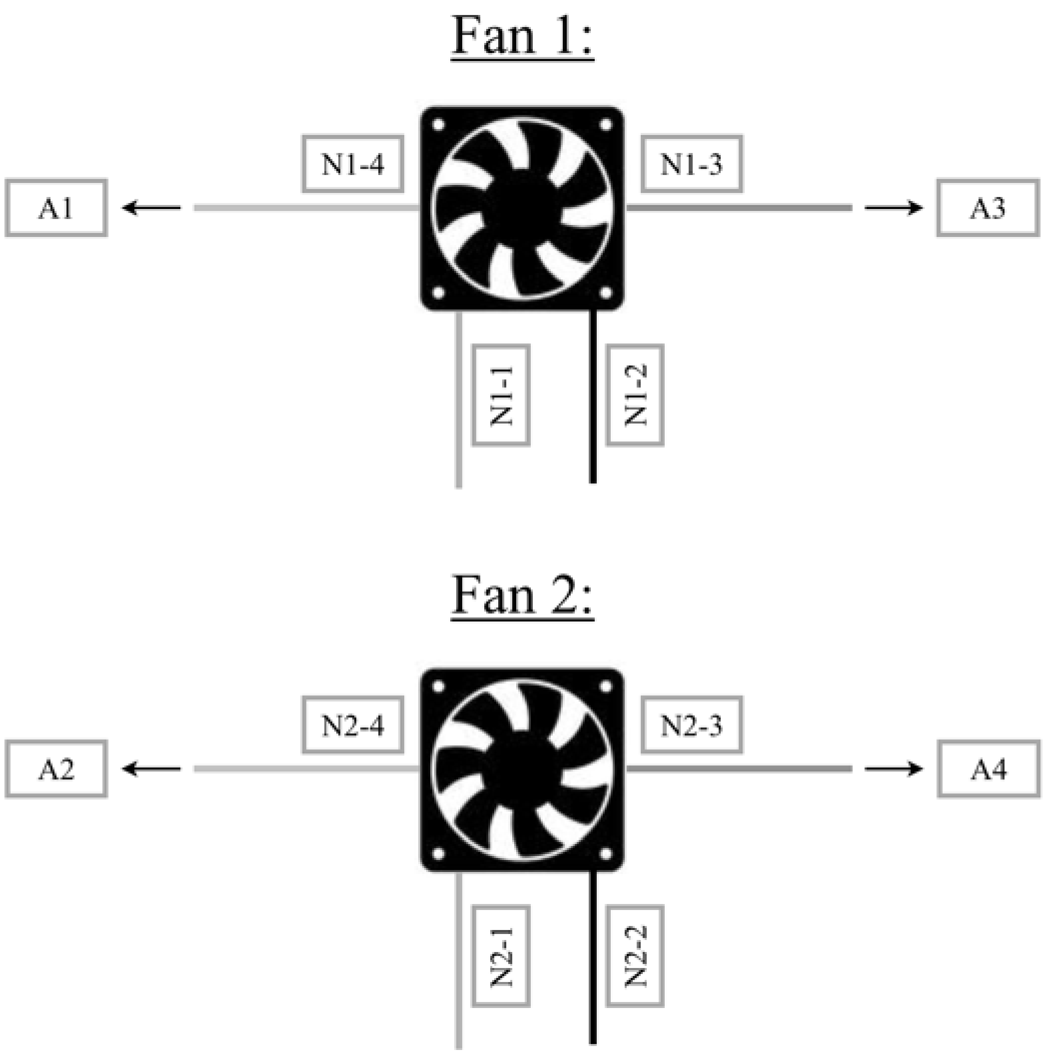


Fig 21. A diagram of the connections needed to supply each fan with power. The red and black wires are connected to power and ground as shown. Each fan will be connected directly to two a different wires from the power supply. The blue wires (N1-2 and N2-2) will be wired using the circuit outlined in Figure 20. The yellow wires (N1-1 AND N2-1) will not be used, and do not need to be connected to anything. They can be cut off so they do not get in the way.

3.4 PCBs

All wiring and circuitry will be done on Printed Circuit Boards.The PCB boards to be used will be 69x50mm in dimensions, with a base material of FR4 fiberglass. Components will be carefully lead-soldered on to these boards. Boards were chosen to be this size for their versatility and that only a couple of components can be wired to one board to avoid confusion.

3.5 Arduino

The Arduino board is a crucial part of the project. It is a microcontroller, essentially a mini-computer, that communicates between the computer and the sensors. It will read in the data collected from the sensors, transfer it to the computer, and send messages from the computer to the sensors. The board to be used is the Arduino Mega 2560. With 54 digital input/output pins, 16 analog inputs, and a 256 kB flash memory, it was chosen for its large number of ports to connect to all our sensors and its large memory capacity.

4 Sensors

For this undertaking to be scientifically relevant, accurate measurements must be made for it to translate into real life applications. Sensors are essential to the wind tunnel as it is how measurements will be made to the highest possible accuracy in the wind tunnel. In this wind tunnel, there is a total of three operational sensors: strain gauge sensor, pressure sensor, and a temperature sensor. From these sensors, values for lift, drag, wind speed, real wind speed, air density, air pressure, air temperature can be detected or calculated.

4.1 Strain Gauge

The strain gauge is the main sensor used to detect forces of lift and drag on the airfoil. Previously considered devices to detect forces on the airfoil includes a force sensitive resistor and a piezo element sensor. A force sensitive resistor varies its resistance as a function of the pressure being applied. This operates very similarly to a strain gauge sensor. However, extensive testing done on the force sensitive resistor showed it to be an incompatible sensor for this wind tunnel. The fans of different airflow, along with various techniques to amplify the resistance were tested on the force sensitive resistor. The force sensitive resistor was not able to detect small values of force, which would be significant in lift and drag calculations. Its larger size was also not desirable. As such, the force sensitive resistor was rejected.

A piezoelectric sensor is a device which utilizes piezoelectric effects to measure pressure, acceleration, temperature, strain, or force. However due to cost constraints, only the piezo element was available. The piezo element is only capable of detecting vibrations. In addition, the size of the piezo element is large, as a circle measuring over one centimeter in diameter. These two factors make the piezo element an unviable sensor to detect the lift and drag forces on the airfoil.

The strain gauge will be set up on the airfoils which are to be placed in the wind tunnel. This sensor measures the strain on the strain gauge’s foil. The foil is a insulating flexible backing which is embedded with an arrangement of conductive strips in parallel. Connected to the foil, there is an amplifier as well as a potentiometer to adjust the measured values for strain. This sensor can detect physical deformations to the foil, for example, a compression. As the flat surface of the foil is being compressed by an external force (i.e. the foil elongating), the conductors inside the foil becomes narrower and stretched out. This change increases the resistance of the conductors, and from the measured resistance of the strain gauge, the amount of stress can be calculated. Stress can be defined as force over an area, and the measurements of stress can be used to find the magnitude of force as area is the constant value of the product of the dimension of the strain gauge. These values can be changed by the onboard potentiometer. By rotating the knob counter clockwise, the input voltage is decreased, and hence this amplifies resistance being outputted. The strain gauge used in this set up will be the BF350-3AA. It uses 5V of power and outputs 0-3.5V. The onboard chip is Model SEN77631Y3.

4.1.1 Original design

The initial design for the sensors on the wind tunnel involved placing sensors at regular intervals across the airfoil, as well as placing sensors at different points of concavity changes. The strain gauge would be set up in such a manner that the base of the foil would be glued to a point in the airfoil. The other end of the foil will be covered with a thin, non-adhesive material that holds the sensor down. This setup allows the airflow to compress the strain gauges.

Taking values from the strain gauge, a magnitude for force can be derived. The calculation and derivation from sensor will be further elaborated on in the coming sections. As the position for the strain gauge is predetermined in the design process, as well as the various angles of attack, the force on the sensor can be taken as a vector in polar form. This vector can be transformed into Cartesian form.

The airfoils will be approximately 40 mm by 80 mm in dimension from a top view. The airfoils will have a thickness of around 20 mm. All these approximations are due to the variations between the four different airfoils. For calculations involving merely two dimensional aerodynamic forces, there will be five sensors placed on each of the four airfoils There will be two sensors on the top of the airfoil, two on the bottom, and two in the front. All of these sensors will be running down the middle of the airfoil, from the upper back all the way to the bottom back. This is optimal as this minimizes the varying size of the force gradients between each sensor, as there will be one sensor for approximately 20 mm apart from each other. From these five sensors, the net horizontal and vertical forces will be summed from the components of the individual sensors. Lift will be calculated by the difference in force on the top and bottom sections (as they will be directly opposite of each other), and drag will be calculated as the total horizontal force over an area. However as the whole area is not covered in sensors, the force gradient between each sensor will be linearly extrapolated, as added to the net force calculations. In this method, further assumptions will be made that both the left and right side are identically symmetrical in terms of force as well.

This method can also be translated to display force on an airfoil in three dimensions. This can be done including 5 more sensors -- two more on the top, two more on the bottom, and one more on the bottom. This method divides up the airfoil into two additional cross sections, and displays the differing forces on the airfoil in three dimensions.

However, this sensor setup (for both 2-D and 3-D) was determined to be not optimal. This sensor setup leads to unreasonable estimates. The major flaw in this setup is that it does not measure the net drag force of the airfoil. While points on the airfoil are measured, to measure drag over an area, large amounts of approximations would have to be done to obtain a value. This is unreasonable as the purpose of this undertaking is to build a wind tunnel that output precise values of aerodynamic forces. Furthermore, this design is dependent on having a large quantity of strain gauges for measurements to be plausible. This leads to not only financial hardship but also difficulty in wire management.

4.1.2 Current Design

From the previous design, it was determined that for lift calculations to be accurate, the net force must be calculated from the sensors directly. Therefore, the sensors must be separate from the airfoil. In this setup, there will be two dowels supporting the airfoils from the sides. These two dowels will be connected to the airfoil at the geometrical center of one of its sides, and the two dowels will extend outward in such a manner that it is perpendicular to the airflow. The construction of this setup will be further elaborated on in *Construction of Wind Tunnel*.

In this set up, there will be six strain gauge sensors. They will all be in the area of where the dowels connect with the exterior wall for support. As there are two intersections for the dowel and the exterior wall, both sides will be setup identically. At the point of intersection between the dowel and the wall, there will be a pit inside the walls for the dowels to fit into.

In each intersection, there will be three strain gauges. There will be one sensor in the back of the pit. This sensor will measure the horizontal force on the airfoils. This measurement will translate into a numerical value representing the drag force. There will also be a strain gauge sensor on the top of the pit, and another one on the bottom of the pit. These two sensors will be accountable for detecting the vertical forces on the airfoil. This measurement will translate into a numerical value representing the lift force.

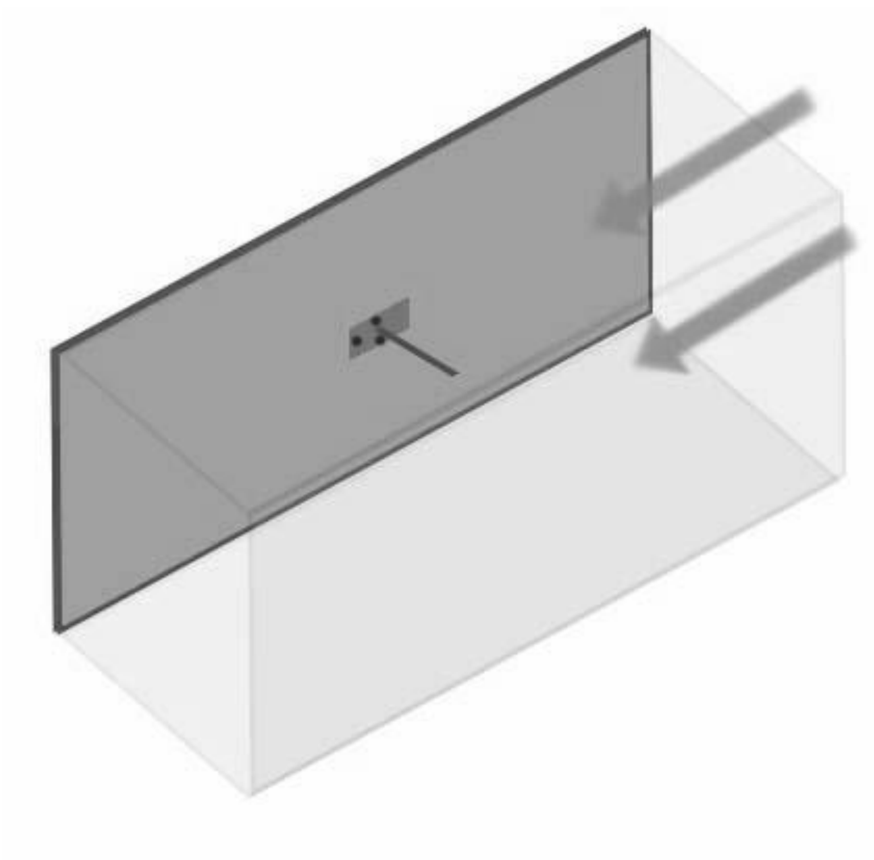


Fig 22. This diagram displays the dowel and sensor setup at one intersection. The airflow is indicated by the direction of the arrows. The dowel is attached to an airfoil (not shown on the diagram), and attached back to the wall in a quadrilateral pit. Inside the pit, the dowel is given space to be affected by the aerodynamic forces. The darkened rectangle represents the pit on the side wall, and the dots in it represent the strain gauge sensors. This diagram is not to scale.

As the strain gauges originally come attached to an onboard amplifier and potentiometer, the sensor needs to be detached from the onboard chip before it is placed into the pit. The onboard amplifier and potentiometer will be connected to PCB at the bottom of the wind tunnel exterior. It will then be soldered to a lengthy wire which will connect to a miniscular hole in the side wall of the test chamber.

The strain gauges will be held using an adhesive to the back wall, the top wall, and the bottom wall of the pit. It will be held in such a way that the front of the strain gauge faces away from the wall. For the sensors detecting the vertical forces on the airfoil, there will be little space between the sensors and the cube end of the dowel. This is because there are two sensors detecting this vertical force -- having both sensors constantly detecting a force makes it easier to compute lift. Forces in both the up and down direction will be fully accounted for, and finding the difference in force at the bottom of the airfoil and the top of the airfoil simpler and more reliable. However for the sensor measuring the horizontal force (ie the sensor at the back of the pit), there will be more space for it to move in the pit. This is because there is only one sensor measuring force in the horizontal direction -- there will be no sensor to detect the forward movement of the airfoil, as it should not happen theoretically. As such, the additional space is to ensure that the force exerted by the cube end of the dowel is not affected any undesired contact.

To ensure that readings from the strain gauges are accurate, there are various precautions that must be taken beforehand. Firstly, the onboard amplifier and potentiometer must be calibrated to the same value. To do this, the knobs on the potentiometer must all be first turned to a maximum / minimum position, then turned a same number of turns to the same angular position. Further testing of this must be done by blowing an identical force on the strain gauge and making sure that similar values are being read between all six sensors.

In addition, the base values may vary between each of the six strain gauges in operation. However, this is not due to variation in atmospheric factors, such as temperature or humidity. These atmospheric factors will result in a variation of the results read, but this variation will be standard across the sensors, as the temperature or humidity gradient cannot vary drastically in such a small enclosed space at room temperature. As such, this standard variation can be accounted for by calibrating the sensors each time before testing begins. Another precaution that must be taken is accounting for the strain gauges that are deformed permanently, which may be a cause of carelessness in installation or by the overwhelming force exerted on the airfoil. If that is the case, the user can either attempt to flatten the strain gauge or letting it be. Either way, its initial measurements will have to calibrated to ensure accuracy.

The last precaution that must be taken is the lift and drag due to the dowel connecting the airfoil to the side of the testing chamber. This can be accounted for by conducting airflow tests without an airfoil, but still leaving the dowels inside. Theoretically, it should not generate a force for lift as it is perfectly symmetrical in design. However there will surely be a force observed for drag. These values must be taken into account in the calculations of aerodynamic forces of the airfoils.

4.1.3 3-D Extension

The setup described above will result in the simulation of two dimensional forces on the airfoil -- the net drag force and net lift force. In order to simulate the variation in these forces, the sensor system in this wind tunnel must measure in three dimensions. For this to occur, modifications in sensor setup and sensor calculation must be made.

To translate the 2-D sensors to detect 3-D values, more strain gauges are needed. The original 2-D setup will be maintained, still exporting values of net lift and drag forces across the overall airfoil. As the original 2-D method measures from two points, it can be said that the original 2-D method exports the net aerodynamic forces from two cross sections of the airfoil. However, this is not accurate enough to be deemed a 3-D measurement of forces on the airfoil. Hence additional strain gauges must be placed on the airfoil.

As all of the predesigned airfoils have identical cross sections side to side (ie with cuts parallel to the direction of airflow), the emphasis of the 3-D sensor system is not on the variation of the force between each cross section, but rather on forces along a cross section. Therefore, more sensors must be placed down the line of symmetry of the airfoil. This way, measurements of force can be taken at varying curvatures in the middle of the airfoil. With two additional strain gauges on the top, one in the front, and two on the bottom of the airfoil, these values can represent a nice gradient of force throughout the airfoil. Given the net forces from the initial 2-D setup, and the gradients from the sensors among, the 3-D forces can be calculated through a series of linear approximation.

4.2 Differential Pressure Sensor

A method to calculate airflow velocity must be devised. To do this, a differential pressure sensor of MPXV 7002 model will be used. A differential pressure sensor measures the difference between two pressures from two ports on different sides of the sensor. The sensor will give the pressure difference value in pounds per square inch, which must then be converted to Pascals for velocity calculations. For this pressure sensor, suctioning will result in lower voltage output, and pressure will result in higher voltage output. This model has a pressure sensing range of -2 to 2 kPa.

4.3 Temperature Sensor

The analog temperature sensor to be used is the TMP36G model. It measures temperatures within the range of -40 °C to 125 °C to a ±2°C accuracy. This three pin sensor's (positive, output, ground) output voltage will be linearly proportional to the centigrade temperature. To minimize this sensor's disturbance on lift and drag measurements, three holes will be drilled on the side of the test section. The head of the sensor is along with part of the pins will be inside the test section, and the rest of the pin length will be on the external part of wind tunnel, connected by wires to either a PCB board or directly onto an Arduino board. The temperature sensor has been tested with a simple Arduino program at room temperature; its output temperature matches the home thermometer measurement.

5 Calculations

5.1 Lift

The lift calculations will be made from the four sensors attached on the top and bottom of either sides of the test section, where the supporting stick and the wind tunnel exterior intersect. Lift is calculated by the difference in force between the force experienced on the upper part and lower part.

Ohm's law states that

$$i = \frac{V}{R} \tag{6}$$

Where
i = Current (A)

V = True Potential (V)
R = Resistance (Ω)

We also know that

$$i \sim \frac{1}{F} \tag{7}$$

Where
i = Current (A)
F = Force (N)

If the current is inversely proportional to the force applied on the strain gauge, then the potential is also inversely proportional. This force - potential relationship is to be calibrated by placing the strain gauge on a flat surface and applying a known force such as very light weights on the gauge. Then, monitoring the different output potentials from different input forces, a relationship can be regressed between input force and change in potential. This function will then be used during the actual experiment to determine the force on each strain gauge.

The total lift is calculated by

$$L_T = L_{U1}+L_{U2} - L_{D1} - L_{D2} \tag{8}$$

Where
L_T = Total lift (N)
L_{U1} = Force from top left side strain gauge (N)
L_{U2} = Force from top right side strain gauge (N)
L_{D1} = Force from lower left side strain gauge (N)
L_{D2} = Force from lower right side strain gauge (N)

5.2 Drag

Drag calculations are also taken from strain gauge data, calibrated in the same way as lift. Drag will be calculated by

$$D_T = D_L+D_R \tag{9}$$

Where
D_T = Total drag (N)
D_L = Force from left side strain gauge (N)
D_R = Force from right side strain gauge (N)

5.3 Temperature

Temperature will be measured by the temperature sensor. The computer program will first read in the potential at the analog pin, then convert that value to the true potential (with the 5V output) of the analog pin by,

$$V_f = V_i \times \frac{5}{1023} \tag{10}$$

Where
V_i= Initial read in potential (V)
V_f= True Potential (V)

The temperature sensor to be used has a scale factor of 10mV per degrees Celsius. The equation to convert the sensor's potential to temperature is,

$$T = (V - 0.5) \times 100 \qquad (11)$$

Where
T = Temperature (°C)
V = True Potential

To convert degrees Celsius to Fahrenheit, it is computed by

$$T_f = T_c \text{ x } \frac{9}{5} + 32 \qquad (12)$$

Where
T_f= Temperature in Fahrenheit (°F)
T_c= Temperature in Celsius (°C)

5.4 Air Density

Using data from the pressure and temperature sensors, the air density can be calculated by,

$$D = \frac{P}{R \ x \ T} \qquad (13)$$

Where
D = Air density (kgm^{-3})
P = Air pressure (Pa)
R = Specific gas constant. For dry air, the value is 287.05 Jkg^{-1}K^{-1}
T = Temperature (K)

Temperature is converted to Kelvins by adding 273.15 to the value in Celsius.
However, as derived in the introduction, the density of air is fairly constant with negligible changes. At 20 °C and 101.325 kPa, dry air has a density of 1.2041 kgm^{-3}. This is a reasonable approximation to derive an accurate result for the purposes of this experiment.

5.5 Air Velocity

Air velocity is calculated by constructing a pitot tube using the differential pressure sensor, model MPXV Pressure Sensor, a cable, rubber tubing, and a metallic tube. Assuming incompressible flow since there is no change in altitude and using Bernoulli's equation, total pressure is the sum of static pressure and dynamic pressure. That is,

$$P_t = P_s + \frac{1}{2}\rho v^2 \tag{14}$$

Where
P_t = Total Pressure (Pa)
P_s = Static Pressure (Pa)
ρ = Density (kgm^{-3})
v = Air Velocity (ms^{-1})

Rearranging the equation, the velocity of air can be computed by

$$v = \sqrt{\frac{2(P_t - P_s)}{\rho}} \tag{15}$$

The static pressure is measured by the component of the differential pressure sensor perpendicular to the airflow, and total pressure is measured by the component of differential pressure sensor in the direction of airflow. The differential pressure sensor used will already give the calculated difference between total and static pressure.

6 Computer Program

A computer program and a graphical user interface is necessary to accompany the wind tunnel. The computer program communicates with the sensors, obtain sensor data, calculate lift and drag forces from the input data, and display these values alongside with a graphic showing the lift and drag forces on the airfoil using a graphical user interface.

All sensor information is to be sent to the Arduino Mega 2560 board, which is to be connected to a computer via a usb cable. Therefore, to communicate with the board, the program must be written in Arduino language. However, Arduino does not allow for the creation of GUIs. Therefore, after initial musings with various languages, it was decided that the GUI will be programmed in Matlab.

Matlab is a highly technical language with large numbers of functions that allows for complex mathematical computations. It has a support package for Arduino hardware, which is compatible with the Arduino Mega 2560. This package enables us to communicate directly with the Arduino board from the Matlab program. A GUI will be created using Matlab's Graphical User Interface Design Environment, where a GUI is created interactively.

Using Matlab to create a GUI involves extensive use of handles. A variable that holds a handle holds a reference to the object. The handle is passed throughout the program; any variable that needs to be accessed in multiple places can be placed with a handle, and the handle is passed around to all the different functions and callbacks of the program.

6.1 Variables and Functions

Many variables are required within the program. The only global variable in the program will be the Arduino variable used to reference the board. All other variables that must be stored in the handles structure that is passed around the program include:

- Each of the strain gauge's output potentials directly read from the pin and calculated actual potential

- Each of the strain gauge's calculated resistance, calculated from input potentials, circuit resistances, and internal resistances
- Force measurements for each of the four lift measuring strain gauges
- Force measurements for each of the two drag measuring strain gauges
- Total lift and drag force
- Each of the resistor's measured resistances
- The temperature sensor's potentials read from the pin, calculated potential, and converted temperature value
- Each of the pressure sensor's potentials read from the pin, calculated actual potential, and converted pressure measurement
- Calculated air velocity value from pressure values
- Calculated air density from pressure and temperature sensors
- Angle of attack of airfoil, a user input variable

All the resistors, strain gauges, and pressure sensor's ports will be numbered based on their usage and location to differentiate between the same components. Other local variables within functions will be used for local purposes such as loops and temporary calculations.

The Matlab program starts with an initialization function and an opening function that will first define all the initial structure (variables) and the handles object. This will be followed by functions for each button, each input box, each picture, each chart, and (possibly) each graph on the screen. For every one of these GUI components, there is a CreateFcn which has code that executes on the creation of the GUI (when the "run program" button is clicked). Each button has a Callback function which includes code that executes on each user button press.

6.2 Sample GUI Screens

Fig 23. Sample starting screen of GUI that allows users to choose the airfoil they are testing.

A pop up screen will open on execution of the finished program, enabling the user to choose one of the four pre-designed airfoils that is to be tested by directly clicking on the images. The finished program will include images of the real constructed airfoils. This program will be incorporated at the start of the main program.

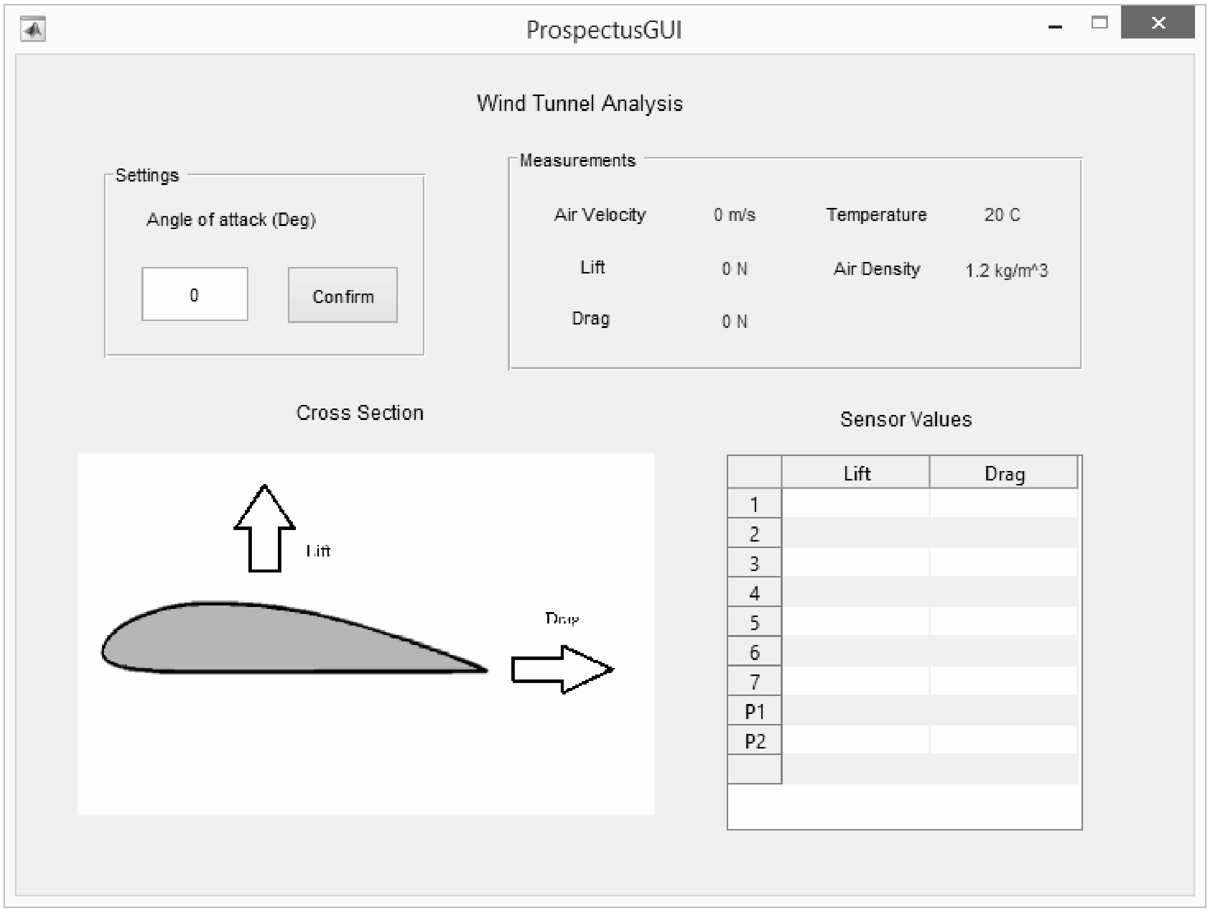


Fig 24. Sample screen of the main program GUI program.

The user will be able to input the angle of attack chosen, which will then be incorporated in the calculations. The values of air velocity, lift, drag, temperature, and air density will be displayed and changed instantaneously as data is gathered, as well as the lift and drag values on each sensor. The two pressure sensors' respective pressure values will be also listed in the table updated in real time. The graphic on the bottom left will include an accurate diagram of the airfoil used that will angle itself with respect to the regular x and y axis based on the input angle chosen. The lift and drag arrows will lengthen / shorten depending on the strength of the detected forces. There will also be another button available for users to change the airfoil, which will take them back to the screen shown in Figure 22 without having to restart the application.

All the calculations to be done are outlined in the Calculations section. These equations and variables will be programmed.

7 Finalization of Project

7.1 Construction

To ensure accuracy in the measurements, the wind tunnel must be constructed as precisely as possible to its intended design. For this undertaking, both mechanical and machine tools will be used to complete its constructions. The cost of these tools will not be added to the total budget, as these tools are reusable, and last for decades to come. Non-reusable construction material such as glue or nail, will be considered a part of the budget.

To build the wind tunnel in a way that minimizes error, the contraction cone, the test section, the diffuser and the drive section should be constructed independent of each other. It is far simpler to construct frames of basic shapes rather than a complicated contraption all at once.

The first step in constructing the wind tunnel is cutting the wood to its exact dimensions. Often wood will come in very large pieces, and cutting them into smaller, easier to handle pieces will be necessary. To cut into dimensions as shown on the design layout, a miter saw is optimal for this usage. Miter saws are often equipped with a laser ruler as well as a protractor, allowing for precise measurements to be made prior to cutting.

After all the parts have been cut, the interior of the wind tunnel needs to be sanded using a fine grit, smoothing out any abnormalities in the wood that may have interfered with airflow. The pits on the side of the testing chamber should be carved in during this step. Using tools such as a small drill press, make small holes for where the wires from the sensors come out.

After the sanding, use wood glue to piece together the parts. Gluing the parts down before securing them with a screw or nail is important, as it allows the screw and nail to be easily aimed and driven in. Hammers and power screwdrivers are needed for this purpose. Most of wind tunnel will be further secured with thin nails at regular intervals. If some angle poses as a difficulty to nail, a nail gun may be used. For tasks such as securing the hinges for the test section opening, a short screw is used to secure the hinge on. It is key to note that when constructing the test section, the diffuser and the drive section, that the legs be installed. This will allow make compiling the four sections far more efficient.

When all four sections are finished, they can finally be pieced together. Combine the wind tunnel two parts at a time: the contraction cone with the test section, and the diffuser with the drive section. Finally combine the two larger part into a wind tunnel. To combine each section, use the designed supports as intended and secure them using the procedure used to secure individual pieces together.

To finalize the construction of the wind tunnel, sand the exterior of the wind tunnel using a medium grit sandpaper. This is to avoid potential splinters from coming in contact with the wind tunnel.

7.2 Tolerance

Given the current budget, time, and technological constraints, 100% accurate force values cannot be simulated from this wind tunnel. There are certain factors that will minimally affect the accuracy of the measurements, resulting in slight deviations from theoretical values. While some of these factors can be accounted, a variety of these cannot, and hence end up affecting the output results.

In this windtunnel, accountable factors that may potentially result in tolerance include the drag forces from the dowels and the fragile attribute of the strain gauge. These factors can be accounted for through a careful due diligence of the setup before each wind tunnel operation. The drag forces from the dowels can be found experimentally, and this value can be recorded and taken into account in the forces calculation for each airfoil. Furthermore, although the calibration of the sensors may vary as the strain gauge may become permanently deformed, a calibration of the sensors prior to each wind tunnel operation can account a significant portion of this issue.

The Reynold’s number is an important value in real life wind tunnel testing. It is a dimensionless value that indicates flow patterns. It is a ratio of inertial force to viscous force. A low Reynold's number indicates laminar flow which is desirable for its smooth and constant fluid motion. On the other hand, a high Reynold's number indicates turbulent flow. In order for our wind tunnel to accurately simulate a life-sized wing of the same geometry as our models, the Reynold's number from the wind tunnel must match the one that would be calculated in real life.

It is calculated by

$$Re = \frac{\rho v L}{\mu} \tag{16}$$

Where
Re = Reynold's number
ρ = Density (kgm^{-3})
v = Velocity (ms-1)
L = Chord length of airfoil (m)
μ = Dynamic velocity (kgm^{-1}s^{-1})

This means that a decrease in size by x times must be followed by an increase in velocity of x times to achieve the same Reynold's number. However, this is impossible to achieve with the constraints of our budget and building materials. Suppose the two fans placed side by side of 110 cfm each will give a total airflow of 220 cfm (which is not realistic). The maximum velocity generated from an online calculator is 12.81 ms^{-1}. With a chord length of 0.0843m, the calculated Reynold's number for our airfoil is approximately 76,011. A real life plane flying at a velocity of 250 ms^{-1} with a chord length of over 6m will have a Reynold's number of over 100,000,000. Therefore, the results obtained from this experiment are solely for demonstration purposes.

Other factors that may have induced tolerance includes various obstructions to airflow inside the wind tunnel. Inside the wind tunnel, there will be a pit, there are sensors and there is a wall, which results in a boundary layer. The boundary layer causes the wind to flow in an irregular manner near the walls, and hence accurate measurements cannot be taken near the wall. All of these impediments to airflow disturb the values given by the wind tunnel simulation.

7.3 Production Schedule

*Production will begin on December 19th, and run for most days during the Winter Break
**At the end of each day, all the work done that day will be tested so that problems can be dealt with as soon as possible
***Record all problems and changes in notebook as work progresses

Dates	Goals	Notes
Dec 19-24	1) Wiring components on breadboards	Order: strain gauge, pressure sensor, temperature sensor, 7 segment display, fans
	2) Testing with the appropriate code	*steps will be completed for each component in order to minimize human error
	3) Soldering onto PCBs	*each component will be tested after it is

		soldered as well
	4) Adding code to full program	
Dates	Goals	Notes
Dec 25-26	Break!!!!	Christmas and Boxing Day
Dec 27-31	1) Cutting all the pieces of material precisely	*all pieces will be measured multiple times to ensure precision
	2) Assembling the pieces appropriately	*inside of the tunnel must be sanded for smoothness
	3) Sealing the wind tunnel and testing for leaks	*airfoils will also be 3D printed during this time, and sanded to size and required smoothness
	Assemble!	*insert electronic components as assembly progresses to avoid insertion issues
		*start with test section and move outward
Jan 1	Break!!!!	New Year's Day
Jan 2-3	1) Complete assembly	*videotape every run
	2) Test the tunnel as a whole, multiple times	
Jan 4-8	Report, and brochure	

In order to monitor our progress, this will be converted into a checklist format, with every action included. For example, the process for wiring a strain gauge would be as follows:

- ❏ wire strain gauge onto a breadboard with the Arduino
- ❏ test circuit with code
- ❏ carefully transfer this circuit onto a PCB board
- ❏ solder all the appropriate connections
- ❏ test the PCB circuit
- ❏ trip all loose ends of wires etc.

7.4 Budget

Materials	Price Per Unit ($)	Number	Total ($)
Microcontroller	14.99	1	14.99
Fan	15	2	30
Airfoil (approx)	5	4	20
7 Segment Displays	1.13	4	4.52
74LS47 Chip	3.9	4	15.6
Strain Gauge	5.8	6	34.8
Temperature Sensor	3	1	3
Pressure Sensor	14	1	14
Small PCB	1.55	6	9.3
Big PCB	4.19	1	4.19
1/2 Breadboard	4.35	1	4.35
Potentiometer	1.1	2	2.2
Plywood (sqr inches)	0.002	750	1.5
Plexiglass (sqr inches)	0.039	85	3.32
Gears	4	1	4
Wires, Resistors, Solder, Sealing, etc.		unknown	9.2
		Total:	$175

8 Sources

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