SKI-1601

Design of Unsteady Wind Tunnel

A Major Qualifying Project Report
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science
in Aerospace Engineering

by

Andrej Samardzic

Jackson Gillenwaters

Thomas Cieslewski

March 25, 2016

Approved by:

Professor Seongkyun Im, Advisor
Aerospace Engineering Program
Mechanical Engineering Department, WPI

Abstract

An unsteady wind tunnel was designed and built for the study of unsteady aerodynamics. The wind tunnel was designed as an open-loop configuration, and an active flow control system was designed as a series of horizontally aligned shutters placed in front of the test section which can block oncoming airflow to create time-varying shear flows in the test section. The wind tunnel was constructed using primarily acrylic and plywood and was run by an axial fan. The active flow control system was composed of four shutters that were held in position and rotated using steel rods and actuators located just outside the shutter frame. Computational Fluid Dynamics (CFD) was used throughout the design processes, ensuring the generation of unsteady flows in the test section.

Acknowledgements

This group would like to thank the following individuals for their help and support throughout the entirety of this project.

Project Advisor	Seongkyun Im

Table of Authorship

Section	**Author**
Abstract	AS
Introduction	JG,AS
Background	
2.1 Wind Tunnels	AS
2.2 Unsteady Aerodynamics	AS
2.3 Active Flow Control Systems	AS,TC,JG
Wind Tunnel Design	AS
3.1 Manufacturing	AS
Shutter System Design	AS,TC,JG
4.1 Shutter System Testing	JG
4.2 Shutter System Manufacturing	JG,TC
CFD Analysis	TC,AS
Conclusions and Recommendations	
6.1 Conclusions	AS
6.2 Recommendations	AS

Table of Contents

List of Figures

1. Introduction

Unsteady aerodynamics involves time-varying flow conditions, and is regularly experienced in real-world operations such as wind turbines, aircraft, and cars. For example, some of today's wind turbines have a height of 140 meters, and its blades have lengths of 60 meters alone. The velocity of wind gusts differ significantly over ranges in height of this magnitude and can introduce fatigue loads on the turbine blades, which can then lead to damage of its components over time. An understanding of unsteady aerodynamic behavior is necessary in the calculation of products' performances and loads, and the innovation for the optimization for conditions they face in their environment [1].

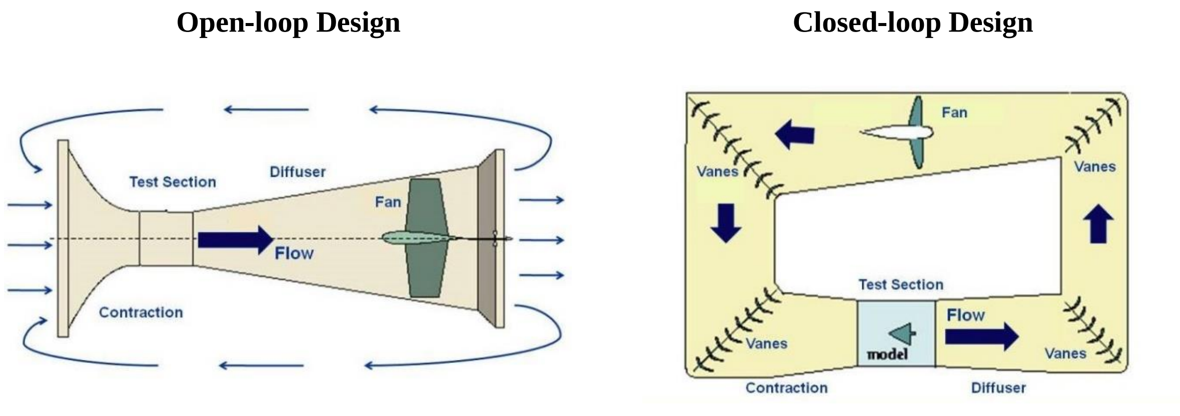
The purpose of this project was to create an experimental facility for the study of unsteady aerodynamics, and to conduct proof-of-concept testing for successful of time-varying flow conditions. To narrow the scope of the project, and give a clear expectation of the conditions the testing would ideally provide, the objective of the wind tunnel was to produce a sinusoidal shear flow in time through the wind tunnel's test section. The flow would provide researchers with added flexibility in experiments: a number of standalone varying shear conditions, or a constantly changing shear flow. In order to successfully achieve the goal, the project was divided into a number of elements: the wind tunnel, the active flow control system, and the testing for proper unsteady aerodynamic conditions.

2. Background

2.1 Wind Tunnels

A wind tunnel is an apparatus that allows researchers to move air over a body to simulate flight and analyze aerodynamic properties of the flow such as lift and drag. Wind tunnels are designed to deliver a consistent, steady stream of air to the test section and minimize turbulence.

Wind tunnels are essential to the study of aerodynamics. Since their founding in 1871 [2], they have undergone a number of iterations in terms of design; the two most common designs are the open-loop wind tunnel, and the closed-loop wind tunnel-- shown below in Figure 1. Both have the same essential components, but their overall design and construction differ greatly. Open-loop wind tunnels draw air from the ambient environment and exhaust it back to the ambient after exiting the fan, while closed-loop wind tunnels create a circuit with air which repeatedly circulates through the tunnel. The closed-loop wind tunnel design delivers improved efficiency and generates less noise, but is more expensive and more difficult to manufacture.



Open-loop Design

Closed-loop Design

Figure 1: Outlining differences in wind tunnel design. Courtesy of NASA

For the project's purposes, an open-loop wind tunnel design suffices performance criteria while adhering to budget and manufacturing constraints and was therefore selected as the chosen design.

An open-loop wind tunnel consists of 5 primary components, listed from left to right on Figure 2 below: a settling chamber, contraction section, test section, diffusing section, and a fan [2].

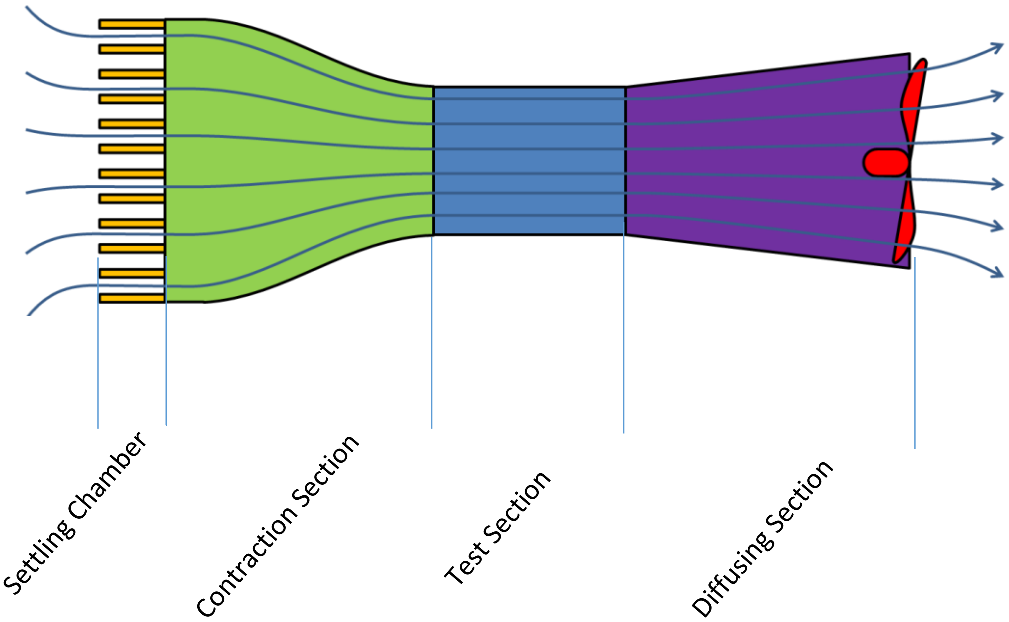


Figure 2: Color-coded model of an open-loop wind tunnel

The first section of any open-loop wind tunnel is the settling chamber, designated in yellow above. The purpose of the settling chamber is to reduce any turbulence in the air flow before entering the converging section. In order to regulate turbulence, the section generally contains a honeycomb structure and a series of woven-wire screens. Honeycombs are effective in reducing lateral turbulence, and common designs include square, circular, or hexagonal-celled cross-sections. Hexagonal honeycombs are most effective due to the smallest loss in pressure over the section. Following the honeycomb is one or more woven screens, which are effective in reducing longitudinal turbulence.

Non-turbulent air then enters the contraction section, denoted by the color green in Figure 2. The purpose of the contraction section is to uniformly accelerate the air flow while minimizing turbulence. In order to smoothly take high volume low-velocity air from the settling chamber and transfer it to a smaller volume with a higher velocity, the shape of the section must be carefully chosen for the desired wind tunnel performance.

Important values such as the contraction ratio, contraction semi-angles, and contour shape are required to be calculated. The contraction ratio (N) is the ratio between the entrance and exit cross-sectional areas of the contraction section, seen below in Equation 1.

$$N = (W_{Ci} \times H_{Ci}) \div (W_T \times H_T) \tag{1}$$

A larger contraction ratio leads to higher flow quality, but research indicated that a ratio of 4 is sufficient in most industrial purposes [3]. The contraction semi-angles (α/2, β/2) are defined as the angles created between the entrance and exit cross-sectional areas of the contraction section. These values can be calculated using the length of the section, and the difference in height between cross-sectional areas, as seen in Equations 2 and 3:

$$\frac{\alpha}{2} = \tan^{-1}((SL_{Ci} - H_T) \div L_C) \tag{2}$$

$$\frac{\beta}{2} = \tan^{-1}((SL_{Ci} - W_T) \div L_C) \tag{3}$$

Contraction semi-angles of approximately 12 degrees provide reasonable flow quality, while maintaining a reasonable contraction section length [3]. The contour shape describes the shape of the contraction section as it moves from entrance to exit. The most effective contour shape holds the form of a third-degree polynomial, as shown in Figure 2, but in many low-cost wind tunnel designs, simple straight-line ducts are used.

Following the contraction section comes the test section, shown in Figure 2 by the color blue. The purpose of the test section is to allow researchers to analyze the airflow over the test object. The primary requirement of the test section is to allow air to flow through it undisrupted. Beyond this requirement, the design of the test section directly correlates to the application of the wind tunnel; factors taken into consideration are test section size, length, and cross-sectional shape.

Air flows out of the test section into the diffusing section, indicated in Figure 2 by the color purple. The diffusing section acts conversely to the contraction section—it takes low volume, high-velocity air, and expands it uniformly across an increasing cross-sectional area to decelerate the flow while creating minimal noise. In order to achieve this, it is important to consider the semi-opening angle (θ/2), which is the angle created between the entrance and exit cross-sectional areas of the diffusing section, and can be calculated using Equation 4 below:

$$\frac{\theta}{2} = \tan^{-1}((SL_{De} - H_T) \div L_D) \tag{4}$$

A semi-opening angle of less than 3.5 degrees provides the greatest efficiency, but research reveals that an acceptable range for this value is between 5 and 10 degrees [3].

Finally, the fan, indicated in the figure by the color red, acts as a catalyst to the wind tunnel system by pulling air through the test section at a desired operating speed.

2.2 Unsteady Aerodynamics

The study of unsteady aerodynamics is defined as the study of conditions in which the flow of air is time dependent. The study of unsteady aerodynamics is of one of great value to the aeronautical industry today; an understanding of unsteady flow field allows researchers to assess and improve a product's performance in real-world conditions. Major examples of industries in which unsteady aerodynamics have become of great importance are in the automotive, aviation, and renewable energy industries, particularly with wind turbines.

The goal of the current unsteady aerodynamics study is to gain an understanding of how changes in shear flow affect an object's performance in both immediate and long-term timeframes. This includes the effect on aerodynamic performance such as lift-to-drag of an airplane flying in unsteady conditions, and the aforementioned example of a wind turbine under unsteady conditions and the introduction of fatigue loads which can lead to component damage.

There have been very few established test facilities dedicated to the unsteady aerodynamics study and analysis of the unsteady flow behaviors. The development of such facilities could lead to further growth in the field of unsteady aerodynamics and optimization of products, leading to highly efficient operation of aerodynamic objects in the future.

2.3 Active Flow Control Systems

An active flow control system is a mechanism that allows researchers to create unsteady aerodynamic conditions in a wind tunnel. The function of the systems is to be able to take a steady, controlled flow of air after it passes through the settling and contraction sections, and manipulate it to create time-varying shear and velocity disturbances in the test section.

Active flow control systems are critical to the study of unsteady aerodynamic and aerodynamic effects on objects. Research identified two prominent designs: a push system, and a pull system [4]. The push system, also known as a fan-grid design, places a grid of small, low-power fans spanning the cross-sectional area of the entrance to the test section. Each fan is individually computer-controlled to produce a specific air speed, allowing researchers to control air speed at any point in the test section. Below is an image of this design, produced by researchers at California Institute of Technology.

Figure 3: Cal-Tech fan-grid active flow control system

The pull system, also known as a shutter system, uses a series of shutters aligned across the test section, spanning the section’s cross-sectional area, and is designed to resist oncoming flow to produce a velocity gradient. Each shutter is computer-controlled to align perpendicularly with the flow to impose a resistance to the incoming flow, parallel to the air flow to allow the air to pass freely through the section, or at any angle between to customize conditions produced in the test section. Examples of two different shutter system designs are shown in Figure 5.

Figure 4: Left-horizontally aligned shutters; Center-rhomboid-grid shutters; Right- vertically aligned shutters

Shutters can be designed in a number of approaches, each providing different levels of control over the air flow. One method is to have shutters be rectangular in shape and be aligned across the cross-section. Rectangular, parallel shutters allow for the production of shear flow in the vertical or horizontal direction, contingent on orientation of placement. Another method consists of a grid of rhomboid-shaped shutters spanning the cross-sectional area of the entrance to the test section. Rhomboid-shaped shutters are capable of producing shear flow in the vertical, horizontal, and diagonal directions, providing researchers with maximum theoretical flow control among different shutter designs.

In an early analysis of potential active flow control systems to be implemented, it was determined that the wind tunnel will house a horizontally aligned shutter system design for the production of unsteady conditions. This system meets performance criteria while adhering to budget and manufacturing constraints.

3. Wind Tunnel Design

The wind tunnel is composed of five primary sections: the settling chamber, converging section, test section, diffusing section, and the fan. Several considerations had to be made in order to achieve desirable wind tunnel properties. Design criteria for the wind tunnel are listed below:

- Low cost
- Portability
- Ease of manufacturing
- Test section dimensions ($L_T x W_T x H_T$): 24 x 12 x 12 inches
- Maximum operating speed in the test section of 5 m/s

The following sections outline the design of each component of the wind tunnel.

The settling chamber cross-sectional area matches the dimensions of the converging section inlet, and contains a hexagonal honeycomb and a woven-wire screen in order to reduce flow turbulence. A hexagonal honeycomb was used for its efficiency over other honeycomb structures.

Research indicated that sufficient flow quality can be generated using a contraction ratio of $N = 4$ [2], contraction semi-angles of $\alpha/2 = \beta/2 = 12$ degrees, and a straight line duct from entrance to exit of the section. A CAD model of the settling chamber and contraction section is shown in Figure 3.

The dimensions of the inlet were calculated using Equation 5 below:

$$W_{Ci} \times H_{Ci} = SL_{Ci}^2 = W_T \times H_T \times N \qquad (5)$$

$$SL_{Ci}^2 = 12 \times 12 \times 4$$

$$SL_{Ci} = 24 \text{ inches}$$

The length of the contraction section was calculated using Equation 6:

$$L_C = (SL_i - H_T) \div \tan\alpha/2 \qquad (6)$$

$$L_C = ((24-12) \div 2) \div \tan 12$$

$$L_C = 26 \text{ inches}$$

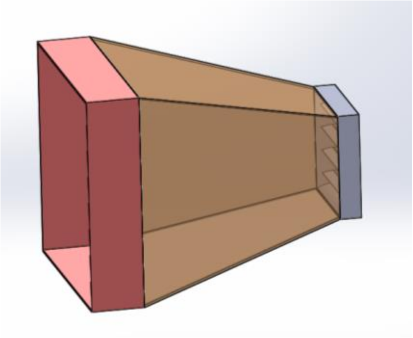


Figure 5: CAD model of Settling Chamber & Contraction Section

Provided the design criteria, the test section will be 24 inches in length, with a square cross-sectional area of 144 in^2. This section will be produced out of ¼ inch Plexiglas for ease of observing while running an experiment.

Research indicates that an acceptable range for the semi-opening angle is between 5 and 10 degrees [3]. Given the scope of the current project, a semi-opening angle $(\frac{\theta}{2}) =$ 6 degrees was used for acceptable flow quality.

The exit dimensions of the diffusing section was calculated using the following equation:

$$SL_{De}^2 = \tan\theta/2 \times L_D + H_T \qquad (7)$$

$$SL_{De}^2 = \tan(6) \times 24 + 12$$

$$SL_{De} = 18 \text{ inches}$$

The final component in designing the wind tunnel system was to select a fan to move air through the system. An axial fan was used for the project due to convention in the field of aerodynamics. Axial fans pull air through the tunnel as opposed to pushing it, creating a smoother flow through the system. The wind tunnel will be used exclusively in the study of low-speed aerodynamics, meaning the fan would operate at a maximum speed of 5 m/s. In order to ensure a speed of 5 m/s in the test section of the wind tunnel, the maximum fan flow rate was an important specification which was analyzed in choosing a fan; the desired flow rate for the purpose of this project given the cross-sectional area of the test section and the desired flow velocity was 0.45 cubic meters per second.

Compiling the chosen designs for each component described above, a CAD model and a CFD simulation were generated for the unsteady wind tunnel system. The CAD model and corresponding CFD results are shown in Figures 4 and 5, respectively.

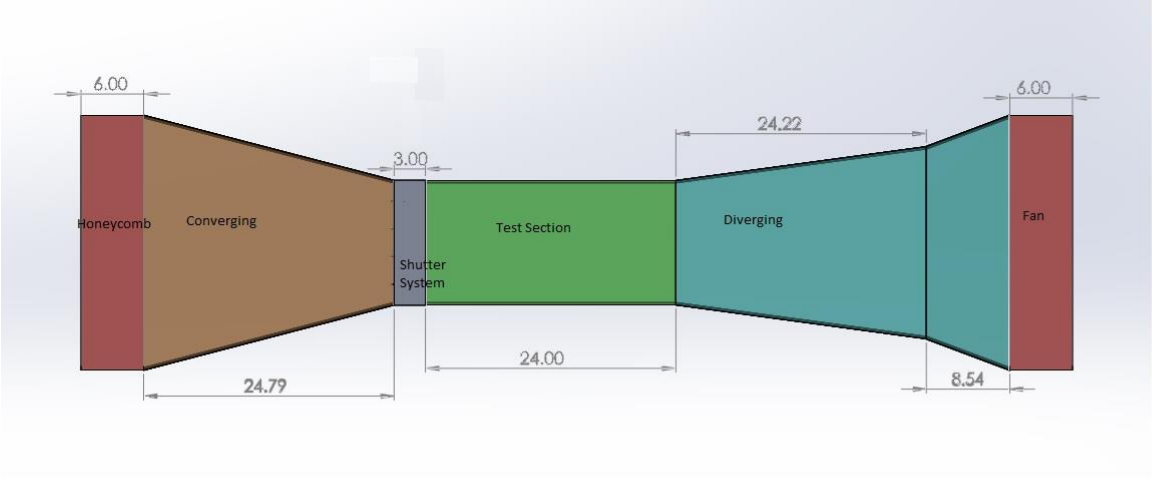


Figure 6: Wind tunnel design generated using CAD

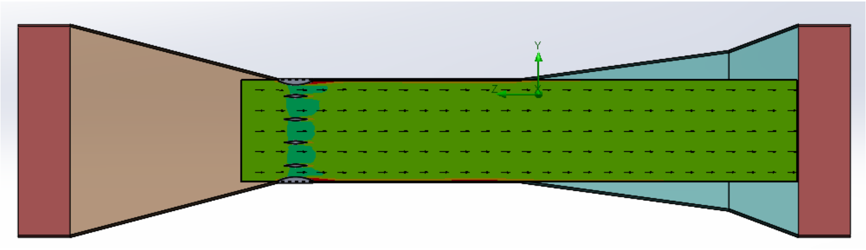


Figure 7: Flow velocity simulated using CFD

Results obtained from the wind tunnel system modelling were promising, with minimal flow separation through the system, and a successful 5 m/s flow speed, indicated by the light green color, through the test section. Positive results in CFD modelling allowed the wind tunnel system design to then be manufactured, keeping in mind the original design criteria of low-cost, portability, and ease of manufacturing.

3.1 Wind Tunnel Manufacturing

Given the scope of the project and allotted budget, the wind tunnel body was manufactured primarily out of plywood and acrylic. The wind tunnel was constructed component-by-component, with sections attached together to complete its construction; a guide for the manufacturing of each section is below:

Settling Chamber

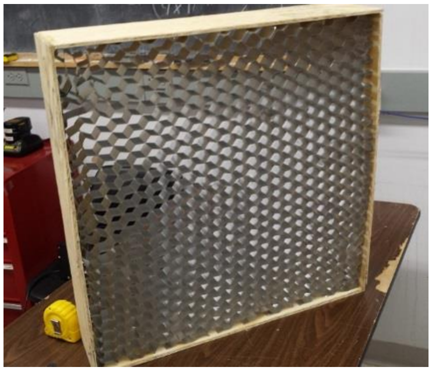


Figure 8: Completed wind tunnel settling chamber

The settling chamber, shown above in Figure 5, was designed as a frame to hold the honeycomb section, which is vital to flow straightening in a wind tunnel. During the manufacturing process, it was determined that the cell size of each honeycomb cell was too large to effectively straighten the flow for the purposes of the project. In order to remedy the issue, a second honeycomb section, with a much smaller cell size, was inserted at the end of the contraction section. The second honeycomb section can be seen below in Figure 6.

Figure 9: Second honeycomb structure, located at end of contraction section

Contraction Section

Figure 10: Completed contraction section, aerial view

Figure 11: Completed contraction section, side view

First, the 1/8 inch plywood sheet was cut into 4 trapezoidal shapes with base lengths of 12 inches and 24 inches with a height of 27 inches, based on prior calculations. Individual pieces were then attached together using wood glue and wooden corner guards. To further increase flow quality, the corners on the interior of the contraction section were lined with duct tape.

Each individual piece was then sanded and coated in a primer and glaze in order to create a smooth surface allowing for higher flow quality.

Figure 12: 1 completed side of diverging section-- Plywood sheet sanded and coated in primer and glaze

With all sides of the section cut and coated, wood glue was used to attach wooden corner guards to the edges of each side of the section, and then to connect the individual sides together.

Figure 13: Wooden corner guard connecting plywood sides of diverging section

Test Section

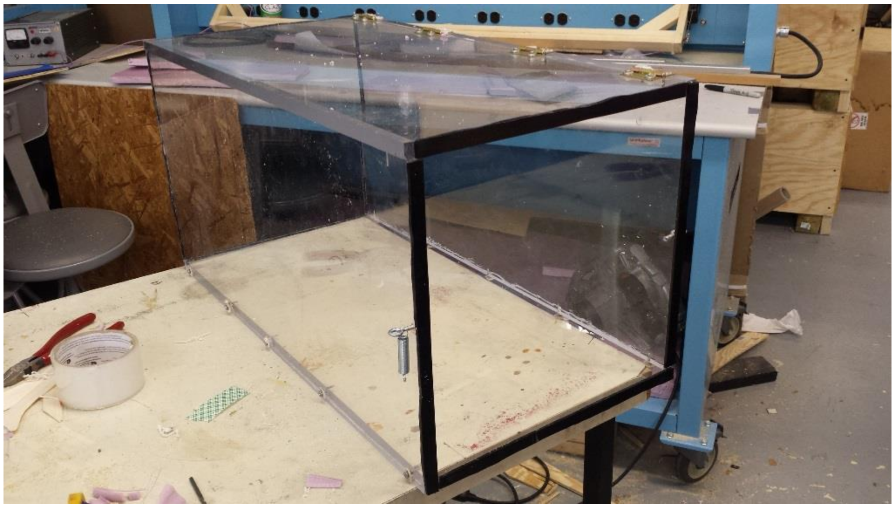


Figure 14: Completed wind tunnel test section

The test section was composed of four half inch thick acrylic sheets measuring 12 inches x 24 inches. The sheets were connected along the longer edges using screws and glue for reinforcement.

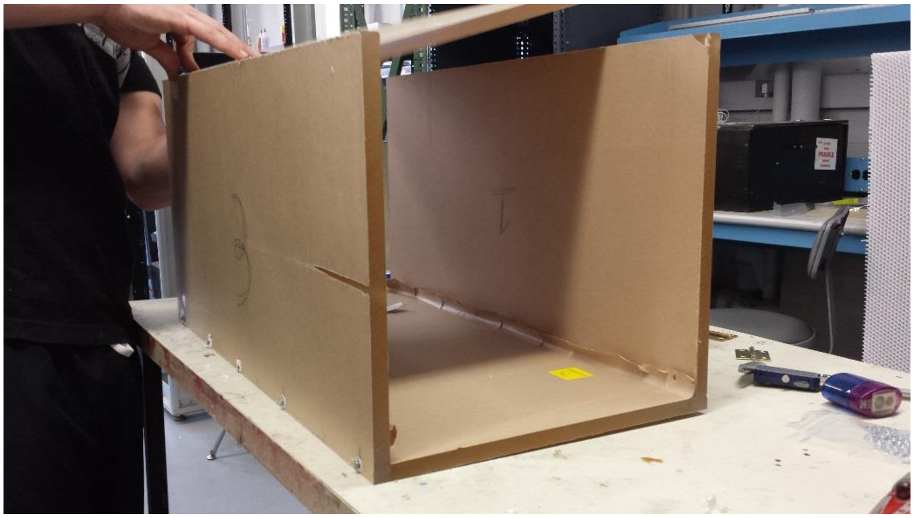


Figure 15: Construction of test section; connecting screws lined with Gorilla Glue visible on sheet 3 of test section

All standalone sides of the test section were connected perpendicularly to one another in this fashion. In order to allow researchers access to the test section, the final sheet was connected to one edge using hinges, allowing it to be swung open.

Figure 16: Hinge connection used in test section construction

To then keep the test section airtight, the other edge was lined with a rubber gasket strip and clamped to the bottom edge of the test section.

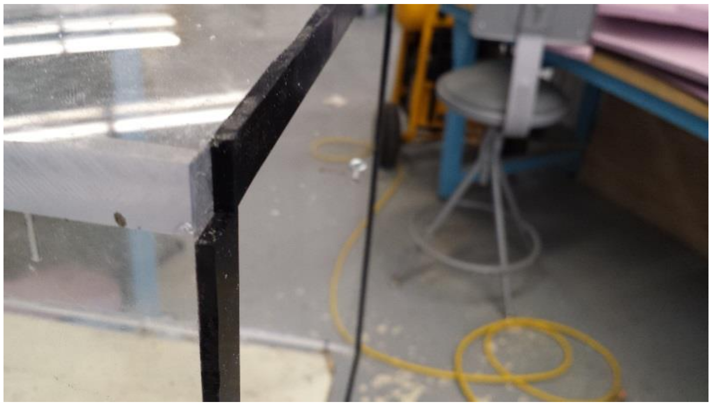


Figure 17: Rubber gasket used to line test section connecting edges

Diffusing Section:

Figure 18: Completed wind tunnel diffusing section

Similarly to the contraction section, the 1/8 inch plywood sheet was composed of four trapezoidal sheets of 1/8” thick plywood coated in primer and glaze. The sheets for the diffusing section had base lengths of 12 inches and 18 inches and a height of 25 inches-- based on prior calculations for the diffusing section. Individual pieces were then attached together using wood glue and wooden corner guards. To further increase flow quality, the corners on the interior of the contraction section were lined with duct tape.

A Cincinnati PF-12 axial propeller fan was then placed at the end of the diffusing section to pull air through the section. The fan had a diameter of 18 inches, and was housed in a metal enclosure measuring 24 inches by 24 inches.

Originally, the team had planned to create a tight fit around the 18 inch fan—having each side of the diffusing section be tangential to the edge of the fan—but were forced to adjust with the fan's delivery. The fan has a pre-installed enclosure with side lengths of 24 inches, and a 'shelf' which extrudes 9 inches from the fan, holding the fan's motor. To adjust, an extension to the diffusing section was built to expand the outlet area of the section, as evident in photos above, and allow room for the motor to remain as it was installed when delivered. Figure 16 shows how the extension fits the fan enclosure to allow comfortable space for the diffusing section.

Figure 19: Diffusing section extension, shown to fit fan enclosure

Assembling Sections

In selecting a method by which to connect the different sections of a wind tunnel, it is important to ensure an airtight seal from one section to the next for smooth, uninterrupted airflow. Given the scope of the project, it was also important to focus on maintaining portability for the entire system of the wind tunnel.

In order to comply with aforementioned criteria, hook-springs were used in connecting components of the wind tunnel together. This method allows the system to be modular—increasing mobility—and if tensioned properly, could create a tight seal between components. To ensure this seal, contact points between primary sections were lined with strips of rubber.

Figure 20: Spring attachment, not tensioned

Figure 21: Spring attachment, tensioned

An image of the completed wind tunnel system structure is shown below in Figure 19.

Figure 22: Fully assembled wind tunnel structure

4. Shutter System Design

The shutter system consists of three main sections: the shutters, actuators, and a frame that houses the other two sections. Design criteria for the shutter system are as follows:

- Strength to withstand operating air flow speed
- Cross-sectional dimensions measuring 11.5” x 11.5”
- Ease of manufacturing
- Low cost

The shutter section contains a stack of four horizontal panels which can be independently rotated to allow or block the flow of air in a specific quarter of the test section. The sizing of the shutters was limited by the test section’s 11.5 inch by 12.5 inch cross-sectional area. Since the face of the shutter section had to be flush with the face of the test section, the shutters had to be slightly less than 11.5 inches long to account for the thickness of the shutter housing. The number of panels selected also was restricted by the cross sectional area of the test section. The design calls for four panels as there are enough to maintain active control over the airflow, while also being large enough to allow a rod to be inserted into either end to facilitate the panel’s rotation. Each panel’s, or shutter’s, cross-section holds an elongated diamond shape as seen in figures 23 and 24. The elongated diamond shape allows air to flow over the panel undisrupted when parallel to the flow (i.e., open). The shaping was influenced by common airfoil models. However, the shape is mirrored over its midsection to allow minimal interference on both the top and bottom of the shutter since its goal is not to produce lift.

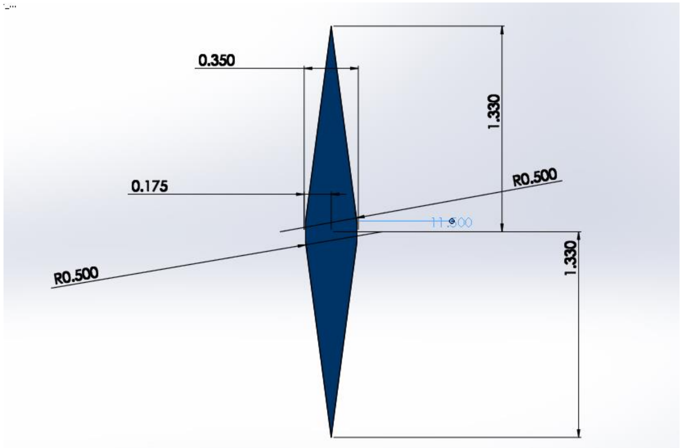


Figure 23: Shutter section CAD model, side view

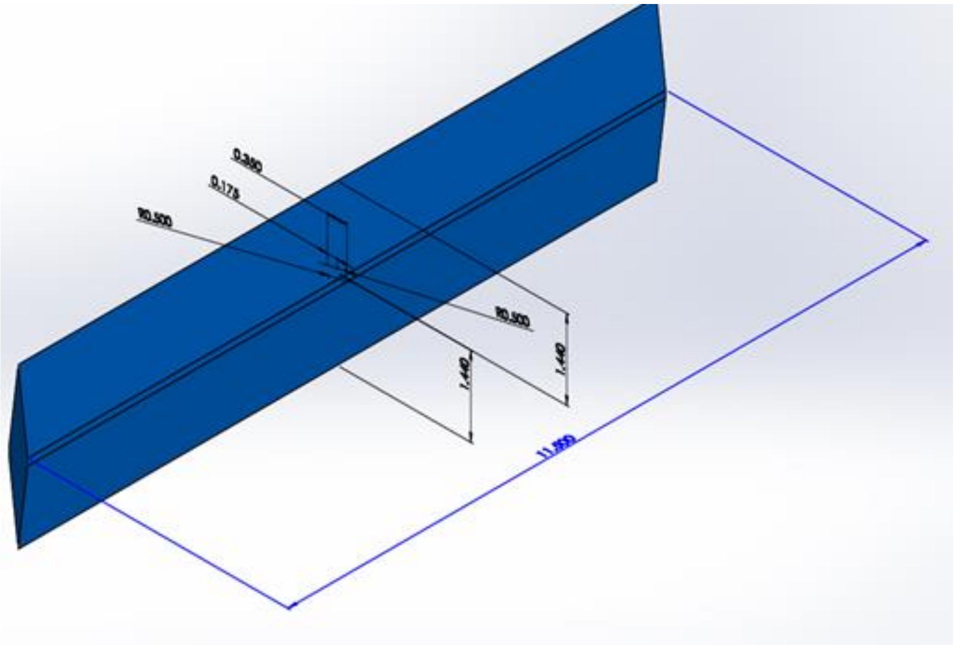


Figure 24: Shutter section CAD model, isometric view

The shutters are encompassed by a frame that lines up with the test section as seen in figure 25, allowing the test section to be completely blocked off if every panel is shut. On the outside of the frame is a series of shelves that holds the actuators up.

Figure 25: Shutter system acrylic frame

The actuators, which are simply motors, are used to control the rotation of the shutters as air flows through the test section. The actuator selection was based off of cost, ease of use, and rotation strength. Given the above design criteria, electric servomotor actuators were selected as they are cheap and easy to use while still maintaining acceptable rotation strength. The servo operates at 4.8-6V, the maximum torque is rated at 0.59 N-m (6.0V), with a maximum angular rate of 375 degrees/second.

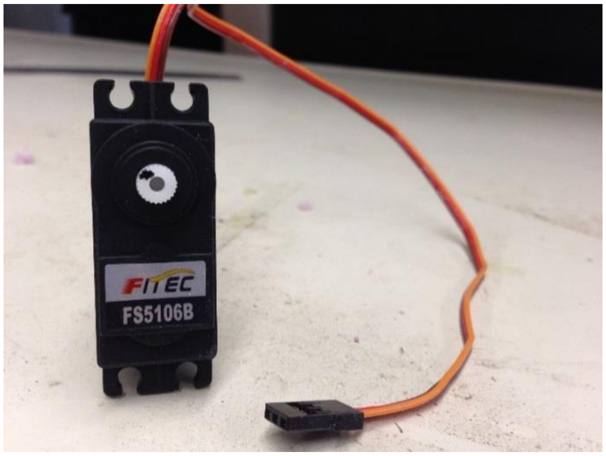


Figure 26: Servo used in Shutter System Assembly

The design of the shutter system offers researchers the opportunity to create shear flow and test objects in unsteady conditions. The shutter system enables the air flow to be carefully controlled before being imaged in the test section. The control offered allows for the testing of more conditions that one would come cross in day to day situations, which is something that is not offered in traditional wind tunnels.

4.1 Shutter System Testing

A model shutter system assembly, comprising of one shutter and servo, was constructed and tested before final manufacturing of this section. The purpose of the shutter test assembly was to ensure stability of the servos through drag forces created on the shutter assembly. The shutter test assembly design was fairly simple, with a U-shaped frame holding a single shutter in place for testing, as seen in Figure 27.

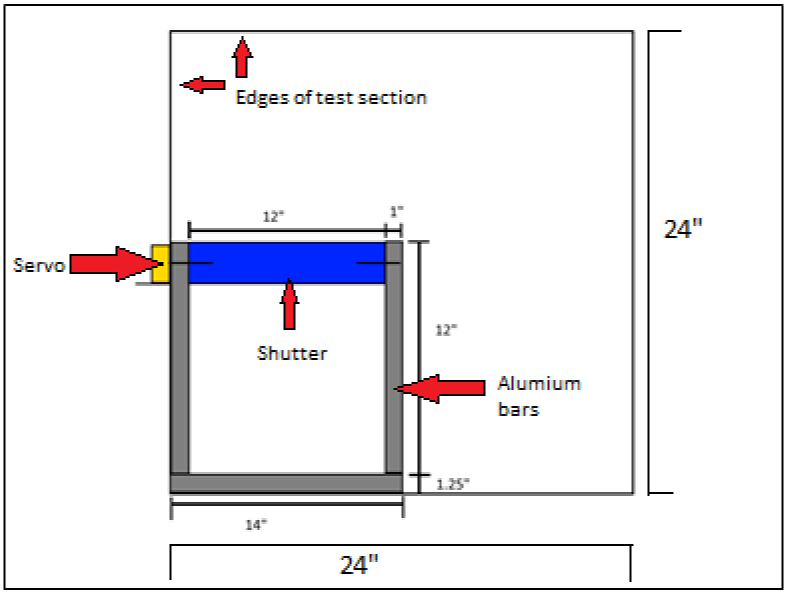


Figure 27: Shutter Test Assembly Design

Figure 27 shows a downwind cross section of the shutter test assembly inside the test section of a wind tunnel. The grey rectangles correspond to the aluminum bars that make up the U-shaped frame, which consists of two upright 12” x 1” x 1” bars, and one 14” x 1.25” x 1.25” bar as the base. A shutter is placed in-between the two uprights, shown as the color blue. The shutter was attached to the sidebars by two pieces of threaded wire. Holes were drilled in the sides of the shutter as well as the bars, allowing the shutter to rotate freely. One piece of the threaded wire was attached to a Servo resting just outside the wind tunnel. The original design for the shutter test assembly was going to be taped to the wind tunnel in order to hold it in place while there was air flow. However, due to the build of the assembly, there was the potential for the entire frame to rock back and forth in the wind because of its profile and low weight. In order to increase stability, a plate was attached to the bottom of the assembly.

There are a few variations between the shutter test assembly and the final assembly. There is only one shutter-servo pair for the test instead of the full four. The test section for the final assembly is also only 12” x 12”, while the test tunnel is four times as large in terms of cross-sectional area. This difference in area throughout the testing process will not cause an inconsistency in airflow quality as excess air will simply pass over the test assembly. Having only one shutter will produce a different air flow through the test assembly compared to the final assembly, as the air won’t be interacting with the other shutters. While there is a discrepancy, the purpose of the test was to ensure stability in the shutter through the force of flowing wind. Therefore, using one shutter in a larger test section was not an issue with this test.

Test Results

The testing run on the shutter assembly involved running the wind tunnel at different speeds while using the servo to rotate the shutter at different speeds as well. The shutter test assembly was secured in the tunnel using a second wooden plate outside the wind tunnel and bolting the two plates together, as seen in Figure 28 below.

Figure 28 (Left): Fastening for Shutter Test Assembly

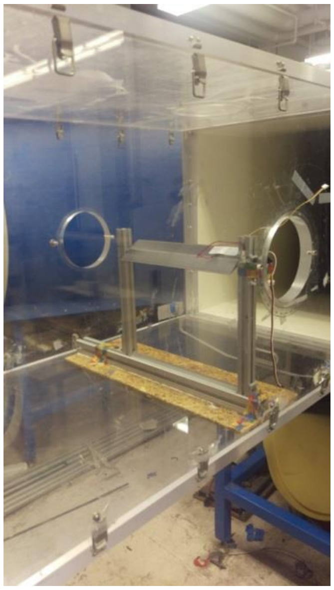


Figure 29 (Right): Shutter Test Assembly Inside Wind Tunnel

The tunnel was run at speeds from 4 m/s up to 7.5 m/s (5 Hz to 9 Hz). Even though the operating speed of the final wind tunnel is to be 5 m/s, the test was run at higher speeds because as the shutters in the final assembly close, the area the wind can flow through is reduced, speeding up the wind. The servo operates at 4.8-6V, the maximum torque is rated at 0.59 N-m (6.0V), with a maximum angular rate of 375 degrees/second. This allowed the testing of the precision (lower speed) and power (higher speed) of the servo. By going through the range of servo speeds at each air flow speed, almost every possible combination of scenarios that would occur in the final wind tunnel was tested.

Throughout the test, there was no visible vibration at all. Further testing was performed using a vibration sensor, as seen in Figure 29, which was attached to the shutter to obtain measurable data. However, the vibrations that the flow created on the shutter were so weak that the sensor was unable to pick up any meaningful data. The lack of significant data combined with the “eye test” led to the conclusion that the servo and shutter combination was fully functional and that the servo could handle vibrations if any did occur during the final experiment. With this, construction of the final shutter system could begin.

4.2 Shutter System Manufacturing

Given the scope of the project and allotted budget, the shutter system was manufactured using acrylic and foam. The shutter system was designed in three steps: first the shutter housing was built, then the actuators were attached, and lastly the foam rollers were added. The manufacturing of each step is outlined below.

Shutter Housing

Figure 30: Acrylic shutter system housing

First, the 1/4"” thick acrylic as cut into four rectangles that were 12” x 3” (sides) and 11.5” x 3” (top and bottom). Then, two of the cut pieces of acrylic had holes drilled into them in order to hold the shutters. Each 11.5” x 2.66” shutter had holes drilled into both ends, as seen in Figure 31. The shutters were then placed in between the acrylic with the holes aligned. A plastic rod was glued through the holes in the acrylic and shutters to keep the shutters in place.

Figure 31: Individual shutter, side view

The remaining two pieces of acrylic were placed to form an 11.5” x 11.5” square around the four shutters. All sides of the shutter housing were screwed together to hold the frame, as seen in Figure 32.

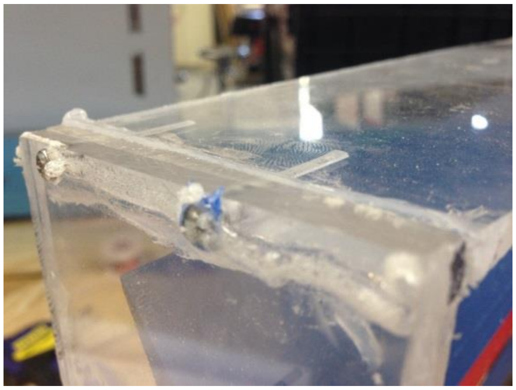


Figure 32: Close-up of screw connection in acrylic frame

Actuators

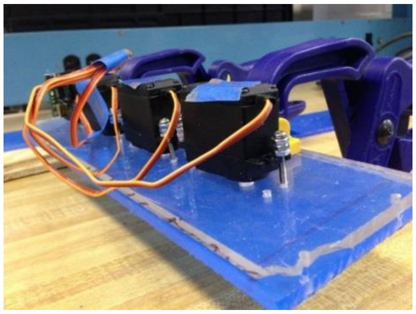


Figure 33: Actuators attached to outside of acrylic frame

For each shutter, an actuator was placed on the outside of the housing as seen in Figure 33. The actuators were connected by the 4-40 steel rods. While one end of the rod was glued in the shutters inside the housing, the other end was inserted into the rotating piece of the actuator. Each actuator was held up by two pins inserted into the outside of the shutter housing, also seen in Figure 33. The actuators are controlled by a Pololu six channel micro controller connected over USB and powered by a DC power source.

Foam Rollers

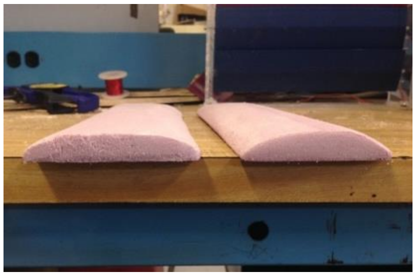


Figure 34: Foam rollers used in shutter system assembly, side view

Two 11.5 inch x 3 inch pieces of foam were cut out of a larger chunk of foam. Then, each piece was sanded down as shown in Figure 34 to fit a .46 inch section at the top and bottom of the shutter housing. The foam rollers were required to fit these small sections at the top and bottom of the housing due to small errors in the 3D printing of the shutters. The software used in printing was unable to produce the thin ends of the shutters, causing each shutter to be slightly smaller than the original CAD model. This left a gap that had to be filled when all the shutters were in a closed position. The rollers are designed to block this gap, as well as be aerodynamic when the shutters are open and air is flowing over the rollers.

5. Computational Fluid Dynamics (CFD) Analysis

Computational fluid dynamics (CFD) simulation software is a valuable tool which allows for the simulation and analysis of fluid flow. It provides users with the opportunity to test flow quality in simulated 3-D designs in order to determine which design would lead to best results.

CFD simulation through SolidWorks was used in designing the contraction section of the wind tunnel. SolidWorks uses the k-ε turbulence model in order to calculate flow conditions. [5] Proper design of the contraction section of a wind tunnel is essential to its construction and its effectiveness as an experimental facility. 2-D and 3-D simulations were ran on the model initially, but based on the symmetry of the model and computational time, a 2-D simulation was used with no effect on overall flow calculations. Background research showed that many low-cost wind tunnels were constructed using a flat contraction section, designated below in Figure 35 as Design 2, rather than one with a curve leading into the test section, shown on the left in Figure 35 which is commonly seen in large-scale wind tunnels. These two conditions were both analyzed in a CFD simulation, with results revealing that a flat-edge contraction section, with contraction semi-angles of less than 12 degrees, as found in research, led to acceptable flow quality for the scope of the current project.

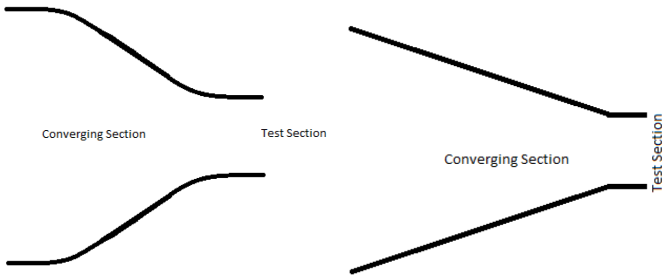


Figure 35: Contraction Section Design 1 (Left); Contraction Section Design 2 (Right)

CFD analysis showed that Design 1 causes a non-uniform flow profile, with air travelling faster in the center of the test section and slower at the edges. This is an unwanted non-uniform flow, as compared to unsteady requirements of the project, air flow would have to be uniform going into the active flow control system, and then manipulated by the system to create a controlled shear flow in the test section. Alternatively, Design 2 allows for a uniform flow to enter the test section, allowing for accurate flow manipulation and proper experimentation.

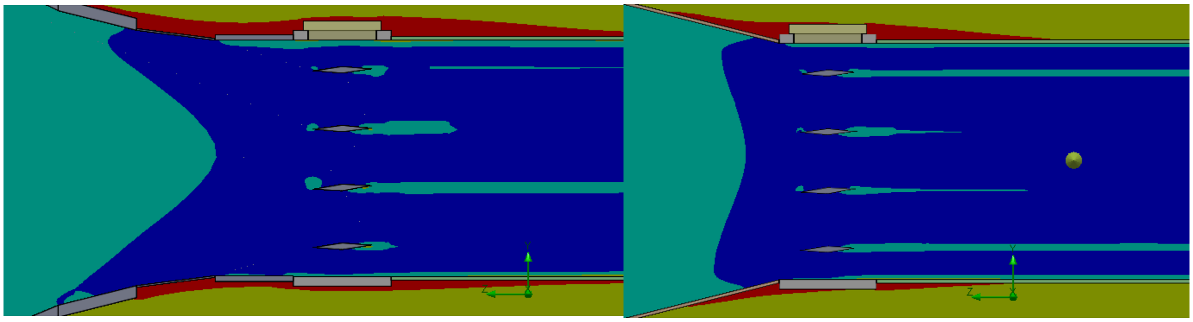


Figure 36: Design 1 flow (Left); Design 2 flow (Right)

Computational design was also used in the design of the shutter system. The shutter system is an 11.5” x 11.5” x 4” structure that is placed at the inlet of the test section, this device uses four horizontal shutters 11.5” x 2.875” with an oblong cross section that will minimal flow separation. These shutters can be turned 180 degrees and are controlled with servos. This allows the user to set up a test procedure for the servos to follow.

The original design had 4 shutters each 11.5” x 2.88”, enough to cover the entire shutter cross sectional area, with overlap between each shutter to allow for no air flow. Under these conditions the CFD results showed that the shutters were able to create sinusoidal shear flow in time. The shutters are extremly thin diamon shapes, to limit their impact on air flow. And the edges of the shutter section created no boundary layer issues connecting to the test section.

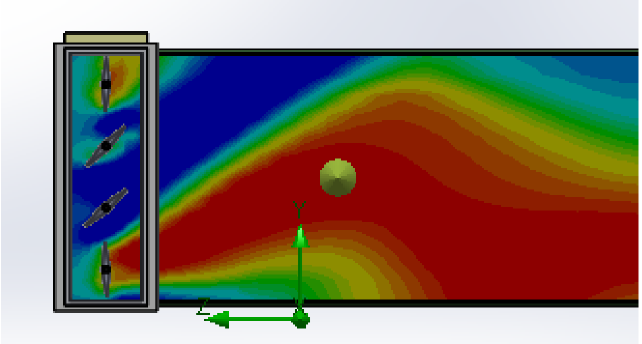


Figure 37: Example of shear flow with original shutter design

There were issues with the manufacturing process of the shutters. The shutters were supposed to have a width of 2.875” but came out to be 2.66” which caused a large gap between the shutters. The shutter assembly required a modification to still be functional. If the shutters cannot create a ”sealed” wall flow will slip past and affect the test section results. The issue was solved by placing the shutters slightly closer together to still maintain the flow blockage which is necessary. If an elliptical shape, cut in half is placed at the bottom and top of the shutter system this allows flow to pass through with minimal impact to the flow itself. The only issue noticed with testing is there approximately (2/3) through the test section the air seems to push back up, causing the opposite shear force. There is a “Prime spot” for testing within the first 2/3 of the test section. Although based on the CFD simulations you can move the testing object back and forth in the tunnel based on test requirements.

Figures 38-41 below depict CFD calculations based on our model, with possible testing configurations, velocity readings in the stream wise direction range from 0-6 m/s. Throughout the CFD testing, using a rectangular computational domain allowed calculation time to decrease from roughly ten minutes to two minutes, there were no differences in test section flow.

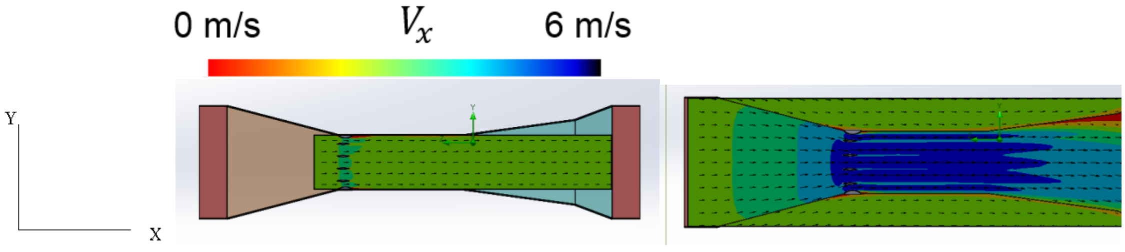


Figure 38: CFD simulation, shutters open uniform flow similar to how most wind tunnels produce a flow field

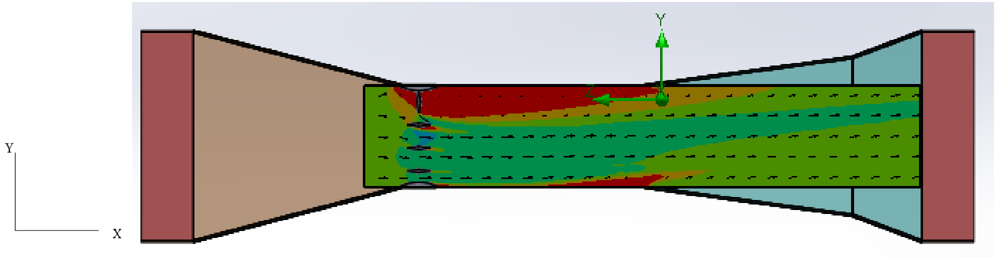


Figure 39: CFD simulation, top shutter closed

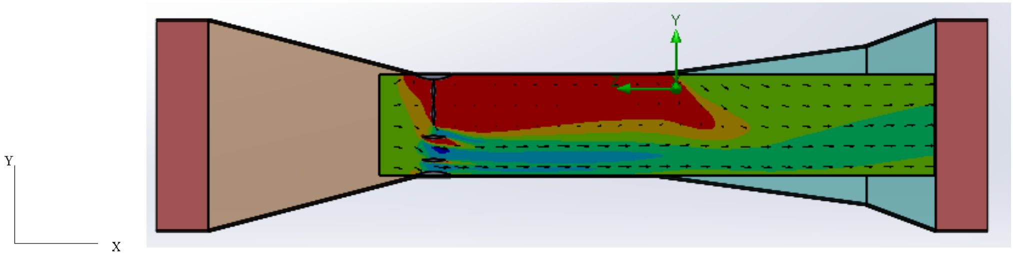


Figure 40: CFD simulation, top two shutters closed

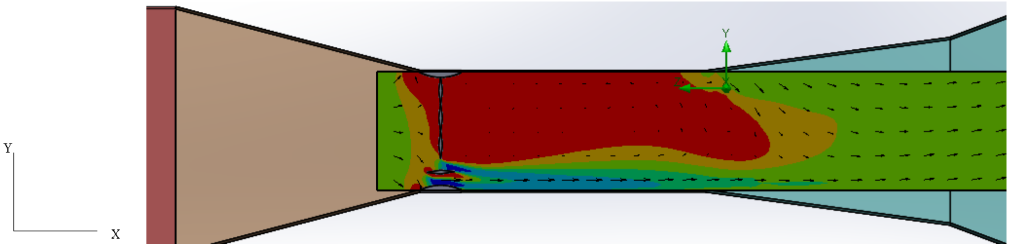


Figure 41: CFD simulation, top three shutters closed

6. Conclusions and Recommendations

6.1 Conclusions

The goal of this project was to create an experimental facility for the study of unsteady aerodynamics, and to conduct proof-of-concept testing for successful recreation of these conditions. The team compiled research on wind tunnel design, the study of unsteady aerodynamics, and the concept of active flow control systems in order to understand the scope of the project and to prepare a building plan. Completed research and Computational Fluid Dynamics (CFD) analysis were then used in the actual construction of the unsteady wind tunnel system.

The wind tunnel structure was an open-loop design and was constructed primarily out of 1/8” plywood for the settling, contraction and diffusing sections, and ½” acrylic sheets for the test section. Wind tunnel components were attached in a modular fashion using springs and spring-hooks as connectors, and the entire wind tunnel system sat on a table for maneuverability purposes.

The shutter system was a series of 4 horizontally aligned shutters aligned perpendicularly to the air flow in the wind tunnel. Housing the shutter system was an acrylic frame measuring 11.5” x 11.5” with two foam rollers located at the top and bottom of the section to fill gaps caused by a manufacturing error and ensure flow quality. Actuators powered the rotation of the shutters through 4-40 steel rods and were then programmed to create specific unsteady conditions for experimentation.

Unfortunately, given the allotted time dedicated to the project, the team was not able to go through the testing phase to verify successful recreation of unsteady conditions in the wind tunnel test section. Alternatively, a flow simulation was completed using Computational Fluid Dynamics (CFD) software whose results looked promising.

6.2 Recommendations for Future Work

While working through this unsteady wind tunnel Major Qualifying Project (MQP), many problems that were not originally anticipated held up the progress of the project. The following section outlines portions of the project that were not completed as well as recommendations for future work on the project and ways to improve what was accomplished.

Omitted from this project—as mentioned previously in the conclusion—is the testing phase to verify recreation of unsteady aerodynamic conditions in the wind tunnel's test section.

Identified areas for future improvement center around the build quality of the wind tunnel. Our first recommendation is to look into the use of higher quality materials in the construction of the wind tunnel sections—notably the settling, contraction and diffusing sections. While our structure suffices for the test conditions of low-speed aerodynamics, we are unsure of how effective our system would be under more intense conditions. Better material would lead to more stability, and could have a smoother profile, leading to better flow quality in the wind tunnel.

Our next recommendation is to purchase a new table or stand for the wind tunnel structure. An important criteria for the system was maneuverability, but due to unforeseen problems and adjustments made throughout the design and manufacturing processes, this was not accomplished. Our completed wind tunnel measured nearly 30 inches longer than the table we intended to use; to solve this problem, we built an extension of the table to support the overhanging section of the wind tunnel. This extension, while necessary, hinders maneuverability of the system. To remedy this, we recommend the purchase of a longer table, ideally with wheels on the legs so that the system can be easily moved and showcased.

Our final recommendation is to recruit or seek guidance from a peer who has a good understanding of Electrical and Computer Engineering (ECE) for the completion of the wiring and testing. As Aerospace Engineering majors, we found this to be complicated and in retrospect, dedicated a lot of our time attempting to gain an understanding of ECE over building our wind tunnel structure. We feel that adding a team member who has an understanding of these fundamental concepts will make the team more efficient, and will allow for more focus on the project and its successful completion.

7. References

[1] King, Rudibert. *Active Flow Control II: Papers Contributed to the Conference "Active Flow Control II 2010", Berlin, Germany, May 26-28, 2010*. Berlin: Springer, 2010. Print.

[2] "Wind Tunnel Parts." *Wind Tunnel Parts*. NASA, n.d. Web. Oct. 2015.

[3] Hernandez, Miguel A. Gonzalez, Ana I. Moreno Lopez, Artur A., Jose M. Perales Perales, Yuliang Wu, and Sun Xiaoxiao. "Design Methodology for a Quick and Low-Cost Wind Tunnel." *Wind Tunnel Designs and Their Diverse Engineering Applications* (2013): n. pag. Web. Nov. 2015.

[4] Gad-el-Hak, Mohamed. *Flow Control Passive, Active, and Reactive Flow Management*. Cambridge: Cambridge UP, 2000. Print.

[5] Williams, David, Wesley Kerstens, Seth Buntain, Vien Quach, Jens Pfeiffer, Rudibert King, and Gilead Tadmor. "Closed-Loop Control of a Wing in an Unsteady Flow." *Closed-Loop Control of Blood Glucose Lecture Notes in Control and Information Sciences* (n.d.): 109-26. Web. Oct. 2015.