Air Flow Unlimited

Final Fall Report

EML 4551C – Senior Design – Fall 2011 Deliverable

Team # 13

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Introduction

Sparking the interest of young minds in the areas of math and science is essential to do so as early as possible so hopefully one day they will become the engineers and scientist of tomorrow.

The Mary Brogan Museum of Art and Science is an interactive museum. There are multiple displays that able to be used by any of the patrons that visit. These displays show all aspects of different principles of physics, from a tennis ball launcher to their Clever Lever. All of these displays are aimed at the enrichment of young minds and showing that the areas or math and science are very exciting.

The Mary Brogan Museum and Dr. Oates of FAMU-FSU College of Engineering have commissioned us to finish an original idea of a display of a wind tunnel. The initial product that is to be expanded upon currently has all the required physical components and assembly to provide air flow through a display case. The wind tunnel display is meant to be added to the Museum’s exhibit upon the completion of the senior design course with which we are enrolled. Previous groups have had trouble finding a strong direction on how to present aerodynamic properties in the current display; we hope to not only determine how best to demonstrate such properties, but to also complete the display and present it to the Mary Brogan Museum.

Problem Statement

For this project we are to take the incomplete wind tunnel and add interactive simulations of different fluid dynamic properties. These properties need to be simple enough for any age to pick up on them immediately and the controls to use the display should require little to no explanation. We are allowed to modify the wind tunnel in any way we see fit but the final product should be ready by the end of the spring semester.

Concept Generation and Analysis

Concept 1 - Airfoil

A staple in visualization of air flow is airfoils; they are used in most wind tunnels to show different pressure regions as the angle of attack changes. For our wind tunnel it is no different, our team will use a simple wind design attached to a rotatable pin which is also contained within a sliding mechanism. The rotatable pin allows for the user to change the pitch angle so that different wakes and pressure differences may be experienced. The sliding mechanism allows for the airfoil to rise and fall as the pitch angle is changed so that the user is able to see the different lift forces that are applied with the different pitch angles. The only issues is since the flow isn't laminar the airfoil has to be adjusted to mostly turbulent flow. This concept allows for a lot of user interactions with the possibilities to adjust the pitch, it also is a very simple concept when it comes to doing air flow. Another benefit is the low maintenance cost of the idea, because there isn't anything that needs to be up kept. An issue with concept is the lack of streamlines that can't be shown so that different wakes due to different pitch angles can't be shown. Also the airfoil isn't going to be switched with another one so there is no variety in using the airfoil; as always space in the air box is also an issue.

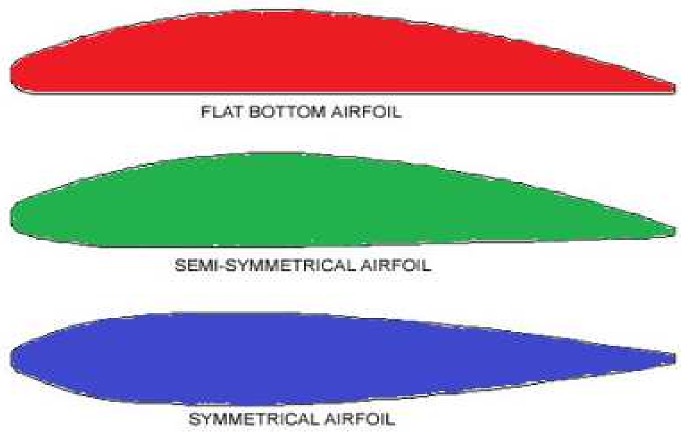

Figure 1 - Various Airfoil Designs

Analysis

The concept of the airfoil is meant to give us a simple but effective way to peak the interest of young minds. Its choice was mainly based on a need to draw in the attention of a young mind as well as demonstrate the scientific evaluation of air flow that we desire. With the presence of a wing it is our goal to associate a scientific lesson or principle in a way that anyone will be able to relate to it, or easily understand it. Lift is a simple idea that most people can grasp, and giving people a wing in a control volume that they can control the lift with a simple input is a great way to integrate higher learning with reap world applications.

Concept 2 - Carts

For this concept our team will supply multiple different attachments that are able to be placed on traditional carts to interact with the air flow. The carts will be stationary on the track with an airfoil or different geometric shape (circle, square, or a triangle) attached to the top of the cart so as the fans generate more flow the carts will be able to move and increase in speed based on the attachment used. This concept allows for a lot of interactive play with kids of all ages as well as helps the user understand which shapes can cause more drag and thus causing the cart to move faster. The concept gives a good visualization for drag forces but is unable to actually display the flow of the air. The concept is also very cost efficient in that it only requires few pieces to be implement. A big issue with this idea is that the user would actually need access to the wind tunnel so that could cause some safety issues if someone could have access to the wind tunnel.

Figure 2 - Cart used in Wind Tunnel

Analysis

The carts are a generally simple idea, and when working with kids the simpler the better. The carts are a good way of displaying drag effects on an object, by showing the force as displacement of the carts, making the learning experience visual. The attachments would be easy to machine out of any material because they are the simple shapes of a sphere and a cube. The attachments would be providing most of the drag force, while the tower and the cart would provide some; the majority of the drag would be from the attachment. The implementation of the carts would be relatively easy, just placing it behind the airfoil experiment and while the airfoil is not in use the carts can be played with. Although there is some use of visuals with the displacement of the cart, an accompanying COMSOL with the carts would be necessary. The COMSOL would be able to help visualize the actual fluid flow over the attachments, not just the forces. The user needs to be able to see how the fluids movement over the system to see how the forces of drag and lift are created. The cart is going to be one of the feature experiments in the wind tunnel because of its simplicity and ability to teach.

Concept 3 - Hand

A different concept compared to actually using an airfoil is to allow access to the wind tunnel and have a user use their hand in place of an airfoil. The air box can have an opening that allows for the user to place their hand into the experimental area and the user then specifies the speed to which they want to flow to act at and uses their hand to feel the different drag and lift forces. The benefit of allowing the user to actually put their hand in the air box is that it lets their hand feel the different forces acting on their hand rather than being told the forces acting on an air foil. The hand concept allows for a tactile response to the forces within the air box, the user feels the change in lift and drag as they change the angle of their hand. The hand idea is also very cost effective in that our team don't need to purchase anything from a third party, all that is necessary is just making modification to the air box. The issue again is safety, if the user is allowed within the air box it could cause technical issues if they decided to touch or move things that are supposed to be. Another rising issue is that the fluid flow isn't actually visualized again, it is only felt.

Figure 3 - Hand Acting as Airfoil

Analysis

The use of the users hand inside of the of the wind tunnel allows for the user to be able to experience the lift and the drag produced by the air flow instead of being told by the display the forces that are achieved from the air flow. The use of the users hand will be able to increase the interactivity of display by allowing the users to feel all the forces as well as play in the air flow. The issues with the hand are that the users will be able to have access to the wind tunnel and because the projected audience of the wind tunnel is k-12, the users cannot be trusted to stay within the guide lines. Most children tend to be mischievous so allowing a child access to the wind tunnel will only result in more issues then learning. The hand will be under further review because of the safety concern with access to the wind tunnel.

Concept 4 - Smoke

Concept 4 uses the idea of smoke in order to expose the airflow lines around the different bodies present in the wind tunnel. Out of all the possible ways of showing the flow and fluid mechanics' phenomena, smoke is the easiest to mount and has a very clear visualization. Air flow tracers would be positioned in front of the blowers so thin lines of smoke would be produced along the air's path. Since the smoke is easily visualized, the changes in the air's behavior due to different bodies' dimensions and aspects could be seen and understood. Another advantage of this concept is that only the tracer's handles need to be in the wind tunnel, the vaporizer could be positioned in the compartment below the tunnel so it would not occupy a lot of space and also would not require big changes in the actual configuration of the tunnel. Furthermore, this project aims to be attractive and fun for kids to use and learn so the smoke would catch their attention for being something that is not commonly seen and for the different behaviors that smoke will have around the objects. Especially in the airfoil case, the attack angle can be changed which will allow the user to play with it and observe the changes caused because of that variation.

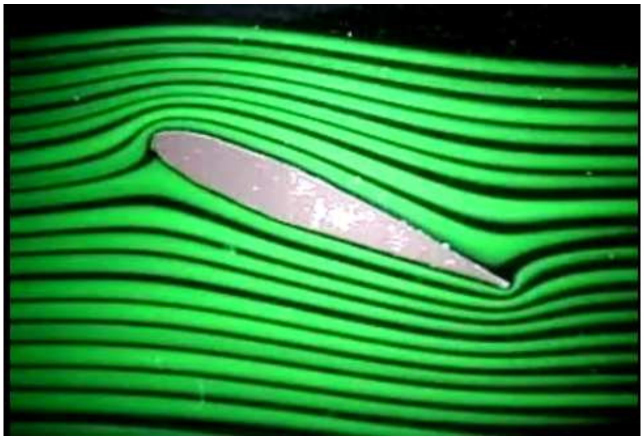

Figure 4 - Flow lines around body.

Figure 5 - Air flow tracer

Analysis

This concept has its strong points based on the ease of seeing flow visualization and in the attractiveness that the use of smoke will have at kid's attention. Also, this concept does not require big changes in the actual wind tunnel design since only the tracer's handle needs to be positioned in front of the blower. Two major issues in this concept are the maintenance and cost due to the constant oil replacement needed because of the vaporizer's high oil consumption. The vaporizer's tank has autonomy of only 9 hours and the oil replacement's cost ranges from $30 to $40. Although the smoke helps in the visualization, there is a problem with the smoke coming out of the tank. An exhauster or some gas absorber would have to be placed in the other side of the tunnel so the smoke would not get to the museum's environment. Together with this, since the tank cannot have big dimensions due to the space available at the museum, would be hard to create a laminar flow in order to have straight smoke lines for visualization what ends up eliminating the idea of using this concept.

Concept 5 - Wake Visualization

The concept of a wake is hard to display without any smoke or lasers so a possible way to allow for wake visualization is to use an actuator and place it behind the airfoil, or what whichever device is creating a wake, and once the turbulent flow vibrates the metal beam the frequency is found and from there a voltage is produced. From that voltage we can display it on the led screens and show that there is a wake created behind the air foil. The concept is able to show the users that an actual wake is created behind different objects, as well as slows for an interactive component with the wakes. An issue with the concept is the space it will take up in our air box might cause issues with other types of visualizations that are going on. The actuator also requires electrical connections which might be an issue within the air box. Without test the actuator our team is unsure if the frequency produced will be significant enough to produce a usable voltage

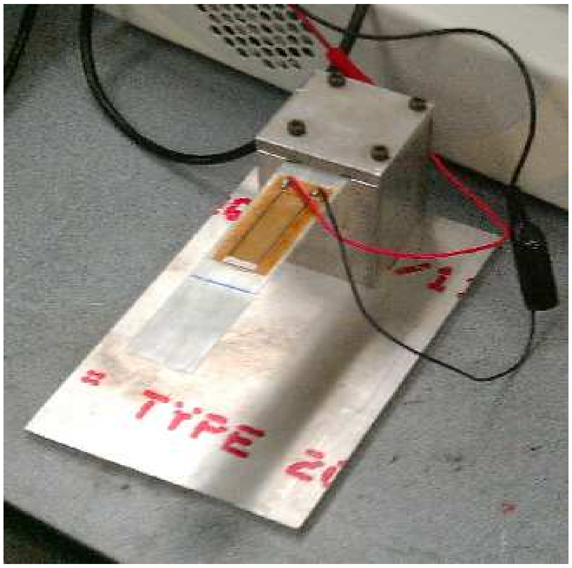

Figure 6 - Wake Actuator

Analysis

This concept is extremely low maintenance. Once installed, it will be capable to run under its own power. This means that other than a quick check to make sure that it is still functioning properly not much more would be necessary. When attached to LEDs, this display may be useable for young viewers. The number of LEDs to light up would indicate the intensity of the wake behind the object. However, due to the limited space inside of the wind tunnel this idea may not be possible. Depending on the number of LEDs that would attached, the larger the voltage that would be required to turn them on. Because of the space constraints this idea will not be implemented at this time.

Concept Selection

		Cost	Maintenance	Space	Robust	Edu.	Simple	Safety	Total
	Weight	0.1	0.25	0.1	0.1	0.25	0.15	0.05	10
Phase 1									
	Air Box	10	9	10	10	7	10	8	8.9
	Towing Tank	1	7	2	8	10	8	5	6.8
Phase 2									
	Smoke	3	1	4	9	10	9	7	6.1
	Cart	8	8	8	7	7	9	9	7.9
	Hand	10	10	8	10	6	10	2	8.4
	Airfoil	6	9	6	8	9	7	8	8
	Actuator	8	9	7	8	5	5	8	7
	10=good	1=bad							

The decision matrix above takes into account all the specifications that are deemed necessary to this project. The first was the cost of implementing each idea. The sponsor does not want to spend a large sum of money therefore; simple inexpensive visualizations should be used. Another major point is that the display should require little to no maintenance. If at all possible keep the maintenance to an annual checkup. Since the wind tunnel is already built the space for the devices is limited. The main point of this project is for it to get used repeatedly by people so being robust must be considered. The display must also be able to teach the user the concept that is trying to be presented. Finally, keeping the wind tunnel simple and not over complicating anything and safe are the final criteria. The matrix itself is a two phase matrix. The first phase was to decide between the towing tank or stay with the current design. The second are the various ideas to demonstrate different flow characteristics.

System Analysis

Air Flow Analysis

The most important step when determining the dimensions and materials of the wing and its assembly is the air speed provided by the air blowers and specific locations in the display. Due to the nature of these blowers the airflow provided varies in both speed as the distance from the exit nozzle increases and distribution vertically as well. In order to achieve an accurate measurement of the airspeed at specific locations a pitot-static tube was used. Using the dynamic pressure measured the true airspeed at specific heights and distances from the blowers could be determined. Using this information everything from the size of the wing and motor, to the materials used to fabricate them could be determined. The most important information was the size of the flow stream, it was most important that the wing did not leave the area in which the air flow was being generated. After this flow stream was located the lowest average velocity was used in the calculation of the lift and other forces generated.

In order to find the flow velocities Equation 1 was used.

$$V = \left(2\frac{P_d}{\rho}\right)^{\frac{1}{2}} \qquad (1)$$

Here V is the velocity of the flow, P_d is the pressure difference from the pitot-static tube, and ρ is the fluid density.

Wing Analysis

Support For Wing

The choice of an airfoil is our primary display method inside the flow box was based on several of our constraint and sponsor requirements. First and foremost whatever we chose had to be low maintenance and simple to reproduce; our display implementation had to be based on some simple and repeatable event and could not incorporate complicated restarts or maintenance cycles. The only way that displays such as these are successful are if they demonstrate their required goal and do it in an interesting and interactive way. This requirement was ascertained from both our sponsor, as well as from observing the designs of similar displays. Another strong constraint that controlled the choice of a wing was that there was already a material constraint of a small display box with large volume air blowers as the primary flow mechanism. Another major constraint is that the display needs to be viewed and comprehended by viewers from ages K thru 12. When all these requirements are evaluated together it made the most sense to choose some simple mechanical event that is related to air flow, as well as something that is easily observable and applicable to everyday occurrences.

The wing application satisfies most of this quite reliably. The concept of lift is something that most minds can comprehend as they have seen airplanes flying and most likely have flown inside an air plane. It is also something that requires no maintenance outside of motor maintenance, there is zero waste produced as you run the display and the reset is as simple as allowing gravity to lower the wing to its default position. One nice aspect of this design is that it takes a simple concept like airflow over a wing can generate lift; which is a concept that many minds are introduced to at a very young age; but it also evaluates how you control this lift by introducing the effect that angle of attack has on these forces. This would also satisfy the requirement that the display must be interactive but also safe to the user. Allowing the user to control the angle of attack will have a direct effect on the lift and drag on the wing which will control if it achieves upward motion and also if it sustains this upward motion.

A major limitation that had to be overcome when choosing display methods is that it would be impossible to show the actual airflow as it is effect by a blunt body such as an airfoil. Any method in which you are able to visualize the flow of a fluid over a specific geometry requires some “waste” material to be introduced to the low, which would violate one of our initial design constraints. Another issue is that with our cost effective flow method which is supplied by the large volume air blowers laminar flow is not achieved, which would be non-ideal for true flow visualization. These limitations can be overcome by using a visual display generated by computer modeling and would serve as the primary information method in the display. This method is to store the visualization of air as it moves over an airfoil and to sync this display with the position of the display airfoil. As the user changes the angle input on the airfoil the electronic display would vary accordingly. This would allow the visualization of true air flow over such a body while compensating for the inherent limitations of the design.

Full Assembly

The first criteria with the construction of the airfoil are that it must only be allowed to translate vertically and not be allowed any other motion. This will be achieved by supporting the airfoil in a block that is completely enclosed by two supports. These supports will limit the motion of the airfoil by ignoring any imbalances in its weighting, and ignoring any effects that the drag will have. This airfoil support must only meet two requirements; it must support of the axis on which the angle of attack will be varied, and it must allow for smooth uninhibited motion in one dimension. By constructing a block with a cylinder removed from the middle and bearings on the sides the wing would be supported in the slot and be able to turn on its axis, and translate up and down due to its lift forces.

The main challenge of the wing design is not adding to much weight to the wing structure itself so that it is able to achieve upward motion based on the lift forces generated. The main complication that arises is attaching the motor to the wing's axis when varying the angle of attack. To overcome this limitation the motor will be supported by the display and not the wing. The Motor shaft will instead be coupled with the wing shaft by two bevel gears offset by 90 degrees. The vertical gear that will be attached to the motor will be fit around the motor shaft and ridged. This will allow the motor to rotate the shaft but also allow the shaft the freedom to translate up and down with the wing. To keep these two gears in contact a small hollow elbow will be attached to bearings on each gear's shaft. This will keep the gears together throughout the operation of the wing display, but will not limit the rotation of the gears. See Figure 7

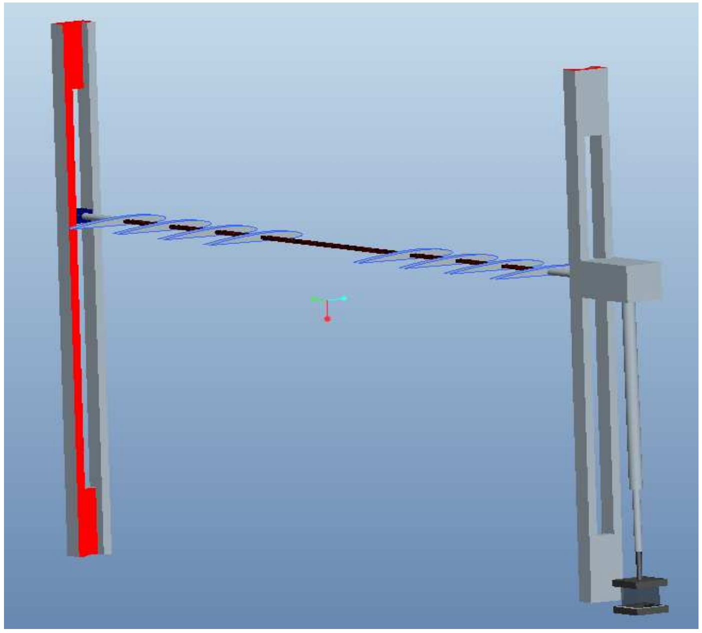

Figure 7 - Full assembly of airfoil.

Lift Analysis

The primary lift application in the wind tunnel display will be the airfoil. The airfoil itself is attached to two side pillars where it will be able to translate vertically. In order to determine whether or not the airfoil will be able to achieve lift, we took the analysis at the worst possible situation the airfoil will find itself in. The location for this to happen will be at the back of the tunnel where the air speed is the smallest. The airfoil must also be able to lift all adjoining features including its own weight. The properties taken for the fluid, in the case of the wind tunnel this will air, are taken at room temperatures.

The first step that must be taken is to find the overall weight that needs to be supported by the weight. In order to do this the materials for each part needs to be selected. It is better to be under weight than over, knowing this the materials to be selected need to be as light as possible. For the airfoil's cross section we shall use balsa wood. The covering around the airfoil shall be made from polystyrene sheets, the extreme thickness of these sheets means that the overall weight of the covering will have little effect on the overall weight. For the boom, another plastic will be use, polyurethane. This same plastic will be used for the bearing shafts, gears, and gear box. The gears themselves will be small enough and will not push the overall weight over the threshold.

With all of these in mind the calculations can be made. The first that will be found is the Reynolds number. This number will represent if there is turbulent of laminar flow. Equation 2 represents the Reynolds number.

$$Re = \frac{\rho V L}{\mu} \qquad (2)$$

Here ρ is the density of air, V is the velocity of the flow, L is the distance from the flow, and μ is the dynamic viscosity. Applying the proper values for air into the equation yields a Reynolds number of 3.7×10^5 this means that flow is laminar. However, due to the close proximity of the fans themselves the flow is turbulent. Next the coefficient to lift will be found with Equation 3.

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \qquad (3)$$

Here F_L is the force of lift that needs to be achieved, A is the planform area, and C_L is the coefficient of lift. Using this and the extreme values the coefficient comes out to be 0.536. The final step is to find the theoretical lift. To do this, Equation 4 is used.

$$Lift = C_L \frac{\rho V^2}{2} A \qquad (4)$$

Using this and knowing that there are going to be two airfoils the total theoretical lift that can be achieved with the airfoil is 0.243lbs. This amount of lift is more than enough to produce a lift that will be seen.

Another key point to be found with the airfoil is the amount of torque that the air flow will produce. This is critical for the motor selection since the stale torque of the motor needs to be greater that the torque applied to the airfoil itself. To find the torque extreme conditions will be taken. This time it will be the pressure difference. Applying the pressure over the area that will experience the pressure and solving for the torque yields a value of 3.057×10^{-3}ft-lb. this being said the motor will need a stale torque greater than this torque which should not be a problem since it is so small. A more detailed calculation can be found the Appendix A.

Drag Analysis

Carts

To find the amount of force was being produced from the wind on to the attachment, basic calculations were necessary. To ensure that the only difference between the two attachments were the shapes the velocity, surface area, and density of air were kept constant. The only variance in the equation was the coefficient of drag, which is based on angle of attach and geometry (for this case the only change was geometry). Seen in the equations below are the actual calculations.

$$F_{dc} = \frac{1}{2}\rho V^2 C_{dc} A \quad (5)$$

$$F_{ds} = \frac{1}{2}\rho V^2 C_{ds} A \quad (6)$$

Here the force of drag for the sphere, F_{dc}, is found with Equation 5 ρ is the density of air, V is the flow velocity, A is the cross sectional area, and C_{dc} is the coefficient of drag for the sphere. The force of drag for the square, F_{ds}, is found in Equation 6 where C_{ds} is the drag coefficient of the square. The drag produced isn't very significant but it is enough to show the difference of drag forces between the two shapes. The difference between the two forces is 0.005 lbf which can be shown by the difference in the displacement of the two carts. With a spring with low enough tension the difference in distance between the two carts can be drastic to convey that the drag forces between the two attachments are significantly different.

Another issue is if the drag force of the attachments would be able to produce enough torque to possibly tip over the carts, but the max torque produced is only $0.038 ft - lb$ so the issue of torque will not be an issue.

Visual Analysis

Monitor

The use of the computer aided visualization will allow the user input to sync with the type of learning experience that the sponsor desires their clients to experience. This will also allow for a high degree of information outside of just achieving lift through the varying angles of attack. The implementation of extra information for clients that may look for a deeper understanding of what is taking place and will be offered the chance learn a great deal from the computer aided display.

The first criteria with the construction of the airfoil are that it must only be allowed to translate vertically and not be allowed any other motion. This will be achieved by supporting the airfoil in a block that is completely enclosed by two supports. These supports will limit the motion of the airfoil by ignoring any imbalances in its weighting, and ignoring any effects that the drag will have. This airfoil support must only meet two requirements; it must support of the axis on which the angle of attack will be varied, and it must allow for smooth uninhibited motion in one dimension. By constructing a block with a cylinder removed from the middle and bearings on the sides the wing would be supported in the slot and be able to turn on its axis, and translate up and down due to its lift forces.

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COMSOL

COMSOL Multi Physics is used to show the different fluid visualizations so that the users of the display will have the ability to see how the working fluid travels over different surfaces like the airfoil, as well as the geometric attachments. COMSOL will take the area of effective working fluid (43in by 6in), the different input velocities (15.8m/s-12.22m/s) of the working fluid (air), as well as the surface which the fluid is flowing over, and create visualizations for them. Some of the COMSOL's going into the project are seen below.

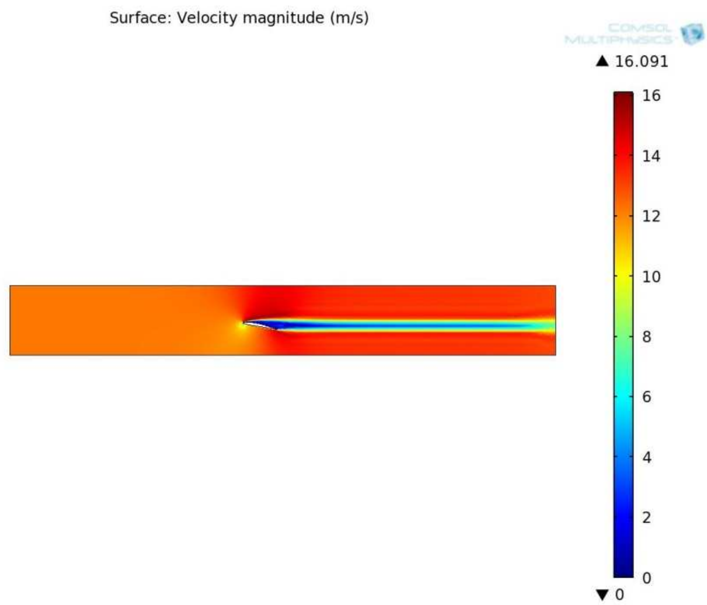


Figure 8 - COMSOL of airfoil.

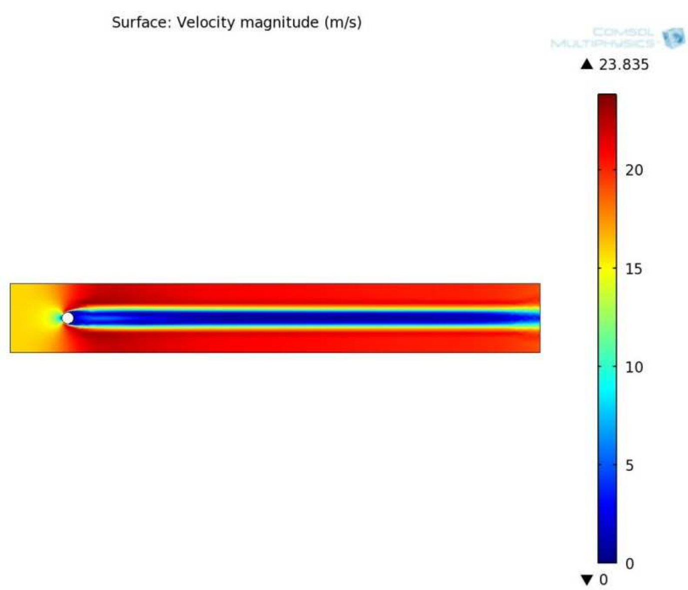


Figure 9 - COMSOL of sphere.

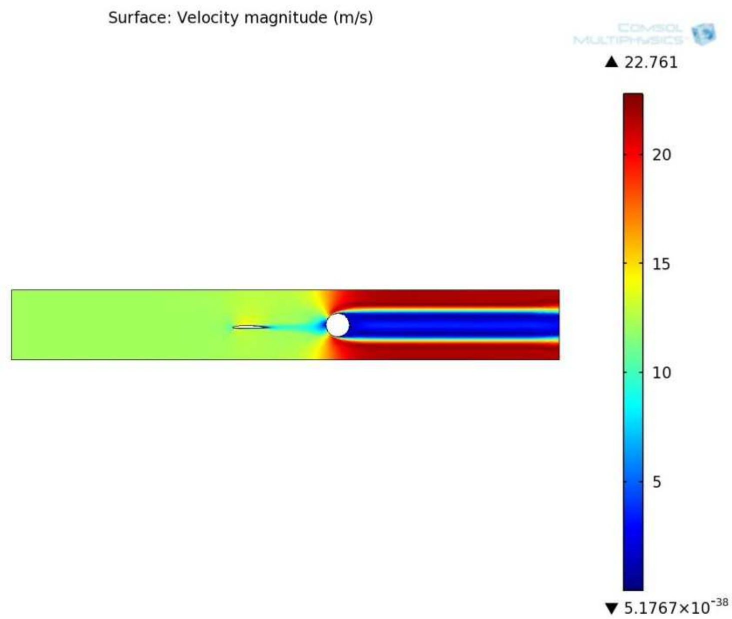


Figure 10 - COMSOL of airfoil in front of sphere.

Figures 8, 9, and 10 above show the varying COMSOL's that will be used to show visualizations in the monitors. The COMSOL's in the actual display will be .gifs so that the user will be able to set the flow develop over time to create the wake, lift and drag of the different geometries. Further COMSOL products can be found in Appendix B.

Side Visualizations

The experiments in the wind tunnel will be briefly explained in the monitors located in the front so the user can quickly understand what is happening. A deeper explanation will be attached to the sides of the tunnel with a better insight in the fluid mechanics aspects for anyone who wants to understand more of the phenomena's.

In the text will have explanations about how the drag varies according to different body shapes, how the lift and thrust works and other how actual calculations were made. The idea is to display a deeper understanding of the experiments to whomever wants, this explanation so will complement the actual explanation and animations that already will be in the monitors.

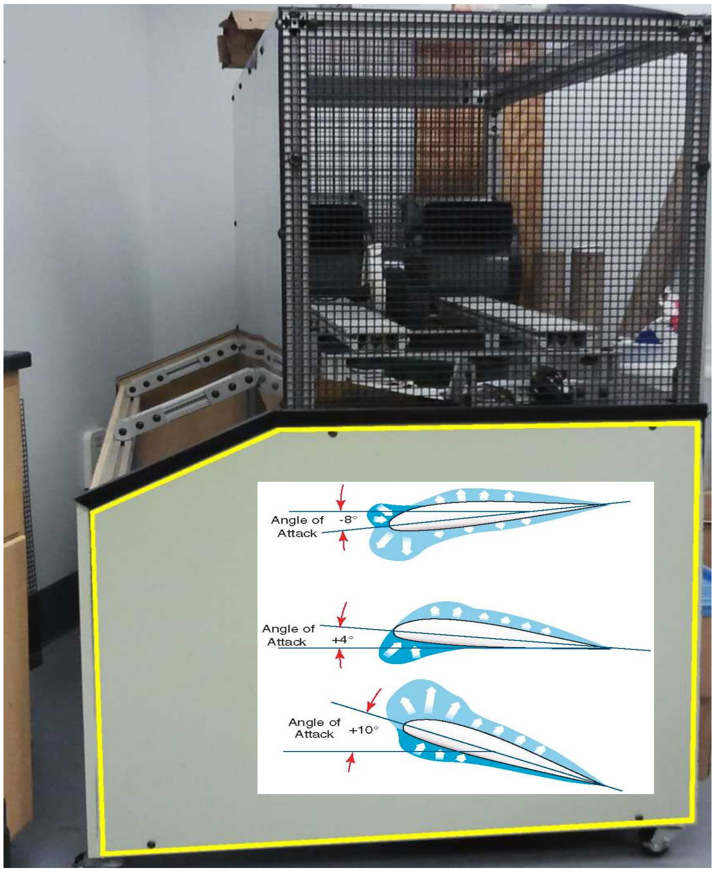


Figure 11 - Possible side visuals.

Mesh Analysis

Analyzing the actual structure of the tunnel, the airflow input entrances of both blowers are blocked by the acrylic plates that protect the sides. This affects not only the air mass volume that goes into the blower but also creates a vibration on it. Since an equal and good air mass input is required for the good and long lasting work of the blowers, there is a need of changing the actual design in order to improve that. The first idea was to drill holes in the acrylic around the blowers' area but the number of holes could compromise the resistance of the structure and also there is the need of a specific type of drill. The second idea was to cut 20 inches of the plate and replace it with an intercropped aluminum mesh with 0.063” wire. The replacement would allow a good air mass flow into the blower and still keep the tunnel safe by avoiding anyone to have access to the blowers. The idea is to change just the blowers’ input area so it does not compromise the visualization of the rest of the tunnel. `

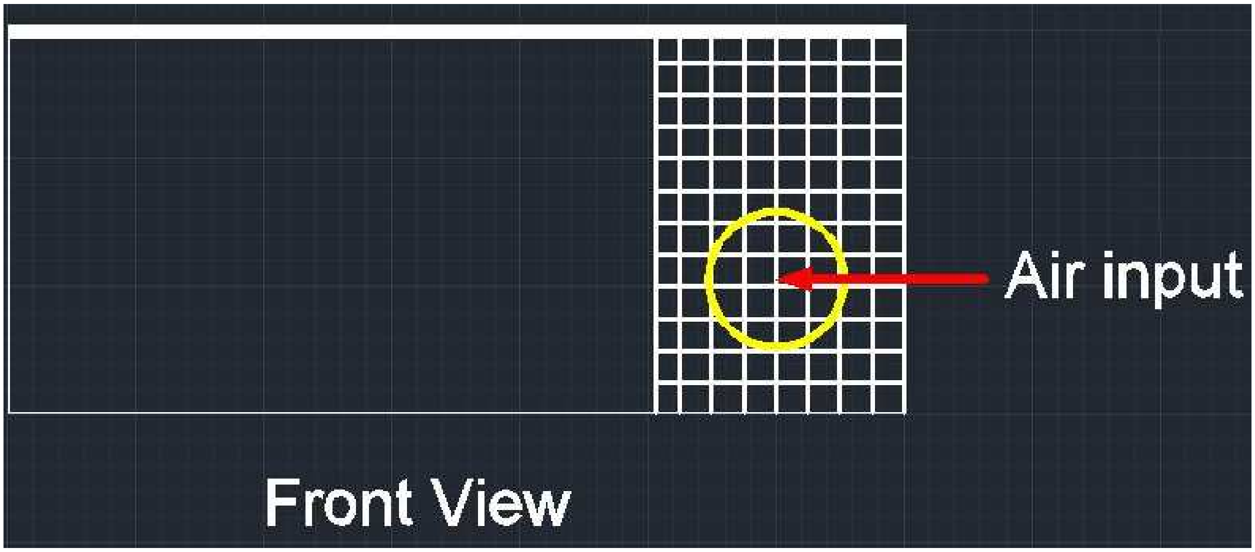


Figure 12 - Mesh at the wind tunnel

Safety

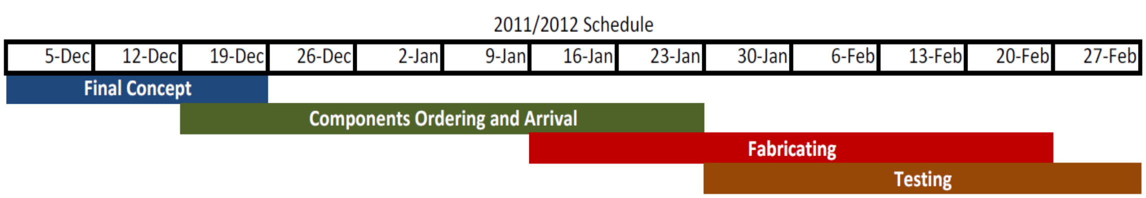
The most important aspect of a design such as this is its safety. Any injuries or failures as a result of the design specifications are unacceptable. First the controls used to input commands to the wing and carts must not have sharp edges, and they must be simple to use; such as a knob. All aspects of the display need to be contained and kept securely separate from any client operating the display. This separation will be achieved through the mesh and plastic panels that already surround the display. The visual monitors need to be covered and re-enforced as to avoid any damage due to misuse which is bound to occur when operated by young children. Also with the operation of young children all edges and mated surfaces on the outside of the display must be covered and rounded off as to minimize injury from contact by any means.

Also important as to the safety of the viewers is the results of the display themselves. It is important that the resetting and operation of the display methods be controlled and peaceful. Loud knocking or collisions may upset some viewers or lead to cyclical failures over longs periods of operation. It is vital that throughout all stages of display cycles that any stage shifts be controlled and gradual. Another important aspect of safety is the noise of the blowers. They must not exceed a volume that would provide discomfort for any viewer, this requirement drives the designs that limit intake blockage and blower securing methods.

Future Plans

The next steps that are involved with this project are ordering of materials, fabricating the parts, and testing. Before the group members leave for the winter vacation the materials should be ordered. Upon arrival from the end of the winter break the fabrication process of each of the components will begin. Once the parts are made any adjustments that need to made shall. The sooner the testing begins the more reliable the final product. Table 1 shows the schedule that we intend on staying with.

Table 1 - Spring Schedule



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Appendix A - Calculations

Following calculations done using MathCAD.

Properties of the air flow

$\rho := 1.2041 \frac{kg}{m^3}$ $\upsilon := 1.983 \cdot 10^{-5} \frac{kg}{m \cdot sec}$ $v := 12 \frac{m}{sec}$ $\mu := 1.983 \cdot 10^{-5} \frac{kg}{m \cdot sec}$

$Length := 20 in$

Wing

$Area := 18 in^2$ $\theta := 15 \cdot \frac{\pi}{180} rad$

$\rho_w := 8 \frac{lb}{ft^3}$

$Volume_{Airfoil} := 1.1828 \cdot 10^{-1} in^3$

$Mass_{Airfoil} := Volume_{Airfoil} \cdot \rho_w$

$Mass_{Airfoil} = 5.476 \times 10^{-4} \cdot lbm$

$\rho_{boom} := 8 \frac{lb}{ft^3}$

$Volume_{boom} := 4.857 \cdot 10^{-1} in^3$

$\rho_{boom} := 0.03 \frac{lb}{in^3}$

$Mass_{boom} := Volume_{boom} \cdot \rho_{boom}$

$Mass_T := \left[\left(4 \cdot Mass_{Airfoil} \right) + Mass_{boom} \right] \cdot 2$

$Mass_T = 0.034 lbm$

Reynolds Number

$$Reynolds := \frac{\rho \cdot v \cdot Length}{\mu}$$

$$Reynolds = 3.702 \times 10^{5}$$

Coefficient of Lift

$$F_L := 0.055 kg \cdot 32.2 \frac{ft}{sec^2} \qquad F_L = 0.121 \cdot lbf$$

$$C_L := \frac{F_L}{\frac{1}{2} \rho \cdot v^2 \cdot Area}$$

$$C_L = 0.536$$

Lift

$$Lift := C_L \cdot \frac{\rho \cdot v^2}{2} \cdot Area$$

$$Lift = 0.121 \cdot lbf$$

$$Lift \cdot 2 = 0.243 \, lbf$$

Gears and Bearings

$Volume_{gear.1} := 0.4107 in^3 \qquad \rho_{gear.1} := 0.03 \frac{lb}{in^3}$

$Volume_{gear.2} := 0.05338 in^3 \qquad \rho_{gear.2} := 0.03 \frac{lb}{in^3}$

$Mass_{gear.1} := Volume_{gear.1} \cdot \rho_{gear.1}$

$Mass_{gear.2} := Volume_{gear.2} \cdot \rho_{gear.2}$

$Volume_{housing} := 0.9478 in^3 \qquad \rho_{housing} := 0.03 \frac{lb}{in^3}$

$Mass_{housing} := Volume_{housing} \cdot \rho_{housing}$

$Volume_{bearings} := 0.0646 in^3 \qquad \rho_{bearings} := 0.03 \frac{lb}{in^3}$

$Mass_{bearings} := 2 \cdot Volume_{bearings} \cdot \rho_{bearings}$

Overall Mass

$Mass_{overall} := Mass_{gear.1} + Mass_{gear.2} + Mass_{housing} + Mass_{T} + Mass_{bearings}$

$Mass_{overall} = 0.08 \cdot lbm$

Torque

$Press := 150 Pa \qquad A := 3.912 in^2 \qquad r := 0.431 in$

$\tau := Press \cdot A \cdot r \qquad \tau = 3.057 \times 10^{-3} \cdot ft \cdot lbf$

Coefficent Circle

$C_{dc} := 0.47$

Coefficient Square

$C_{ds} := 1.05$

Radius

$r := 1.1284\,in$

Length, width

$L_s := 2in$ $W_s := L_s$

Cross Sectional Area Circle

$A_c := \pi \cdot r^2 = 4 \cdot in^2$

Cross Sectional Area Square

$A_s := L_s \cdot W_s = 4 \cdot in^2$

velocity of air @ 0in

$V_0 := 51.837 \frac{ft}{s}$

Velocity of air @10in

$V_{10} := V_0$

Density of air

$\rho := 0.075 \frac{lb}{ft^3}$

Drag for circle

$F_{dc} := \frac{1}{2} \cdot \rho \cdot V_0^2 \cdot C_{dc} \cdot A_c = 0.041 \cdot lbf$

Drag for Square

$F_{ds} := \frac{1}{2} \cdot \rho \cdot V_0^2 \cdot C_{ds} \cdot A_s = 0.091 \cdot lbf$

$F_{dc} - F_{ds} = -0.05\,lbf$

http://www.pasco.com/prodCatalog/ME/ME-6951_gocar/

height above cart

$h := .127m$

Torque generated by drag circle

$\tau_c := F_{dc} \cdot h = 0.017 \cdot lbf \cdot ft$

Torque generated by drag square

$\tau_s := F_{ds} \cdot h = 0.038\,lbf \cdot ft$

Density of aluminum

$\rho_{al} := 2.9 \times 10^6 \frac{kg}{m^3}$

$thick := 4.762 \times 10^{-3}\,m$ $width := 0.0508m$

$Length := 0.13335m$

$V_{baseplate} := thick \cdot width \cdot Length = 3.226 \times 10^{-5} \cdot m^3$

$length_{rod} := 0.25in$

$width_{rod} := 0.25in$

$height_{rod} := 3.8125in$

$V_{sphere} := \frac{4}{3} \cdot \pi \cdot r^3 = 9.862 \times 10^{-5} \cdot m^3$

$V_{square} := L_s^3 = 1.311 \times 10^{-4} \cdot m^3$

$V_{rod} := length_{rod} \cdot width_{rod} \cdot height_{rod} = 3.905 \times 10^{-6} \cdot m^3$

Volume of Al in the Sphere

$V_1 := V_{baseplate} + V_{sphere} + V_{rod} = 1.348 \times 10^{-4} \cdot m^3$

Weight of Al in the Sphere

$Weight_{sphere} := \rho_{al} \cdot V_1 = 39.859 \frac{kg \cdot s^2}{m} \cdot g$

Volume of Al in the Square

$V_2 := V_{baseplate} + V_{square} + V_{rod} = 1.673 \times 10^{-4} \cdot m^3$

Weight of Al in the Square

$Weight_{square} := \rho_{al} \cdot V_2 = 49.462 \frac{kg \cdot s^2}{m} \cdot g$

$$\rho := 1.204\frac{kg}{m^3}$$

$$p_{d1} := 150Pa \qquad p_{d2} := 130Pa \qquad p_{d3} := 90Pa$$

$$v_1 := \left(2\cdot\frac{p_{d1}}{\rho}\right)^{\frac{1}{2}} \qquad v_2 := \left(2\cdot\frac{p_{d2}}{\rho}\right)^{\frac{1}{2}} \qquad v_3 := \left(2\cdot\frac{p_{d3}}{\rho}\right)^{\frac{1}{2}}$$

$$v_1 = 15.785\frac{m}{s} \qquad v_2 = 14.695\frac{m}{s} \qquad v_3 = 12.227\frac{m}{s}$$

Appendix B - COMSOL

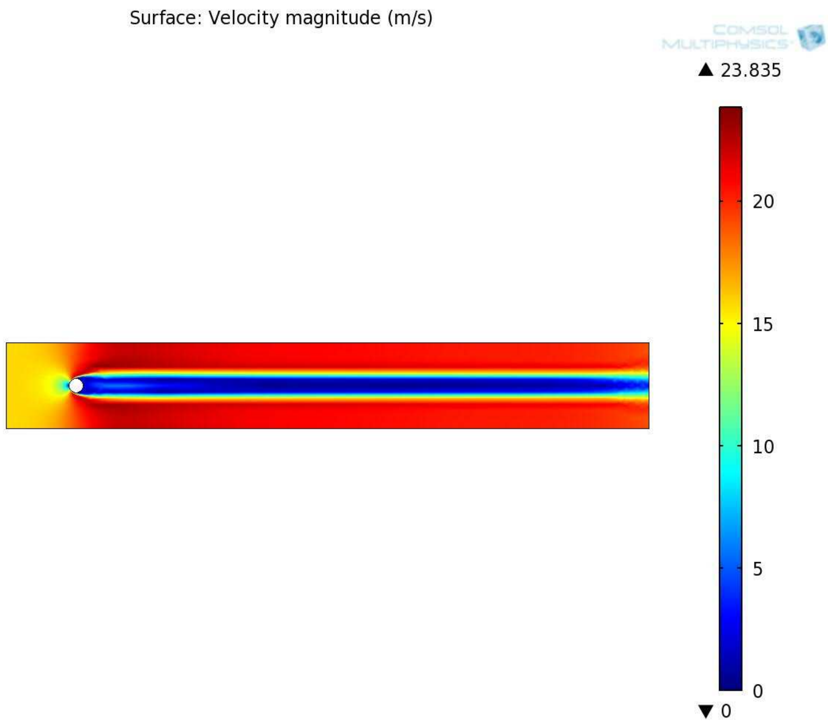

Figure 13 - COMSOL for sphere.

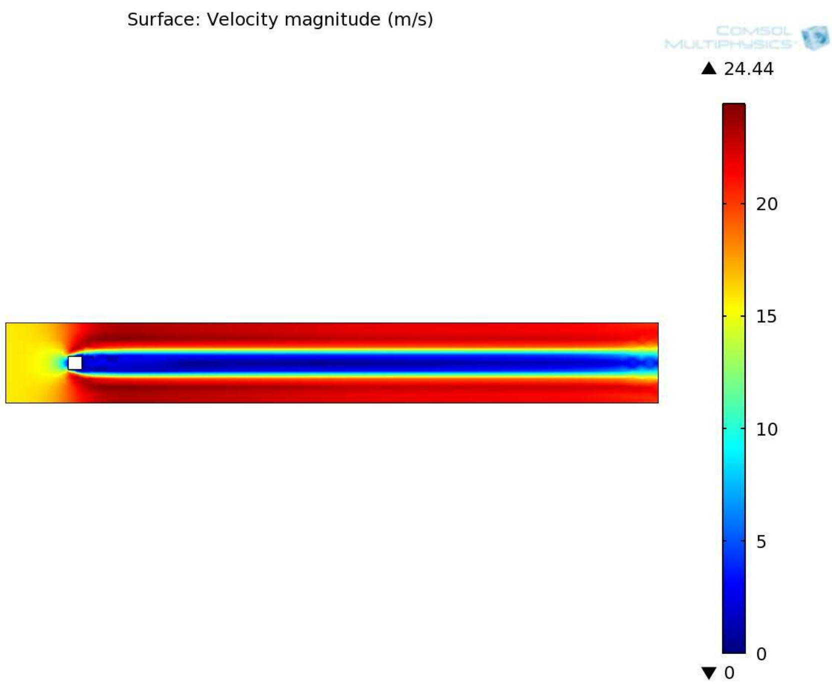

Figure 14 - COMSOL for cube.

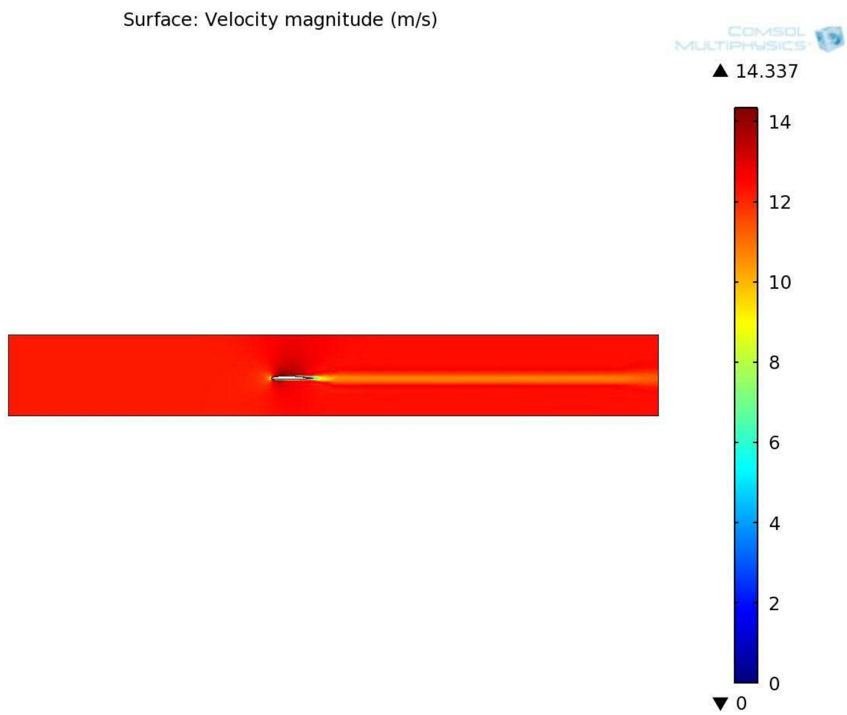

Figure 15 - COMSOL for airfoil at 0 deg.

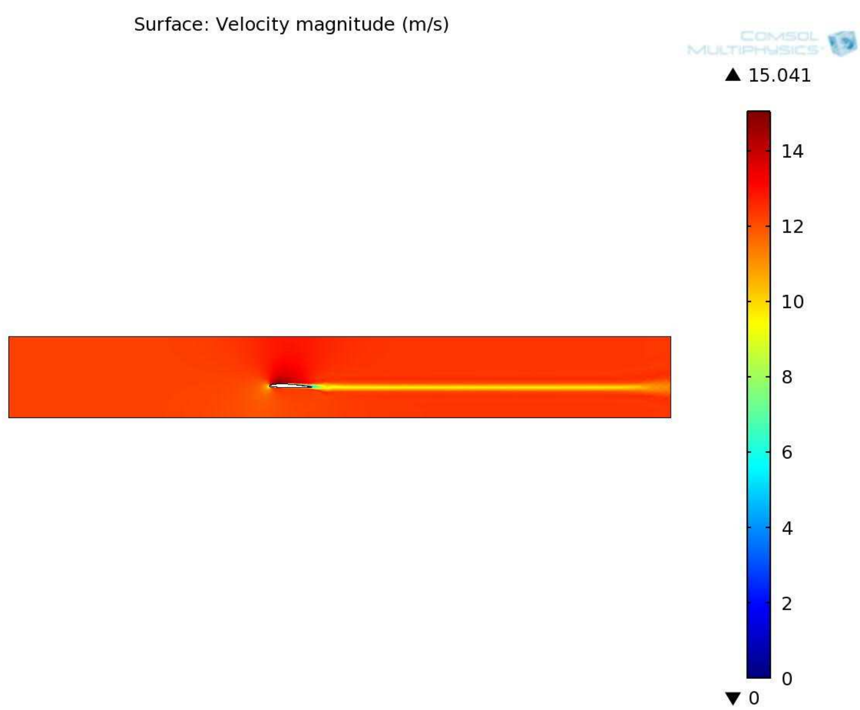

Figure 16 - COMSOL for airfoil at 1.8 deg.

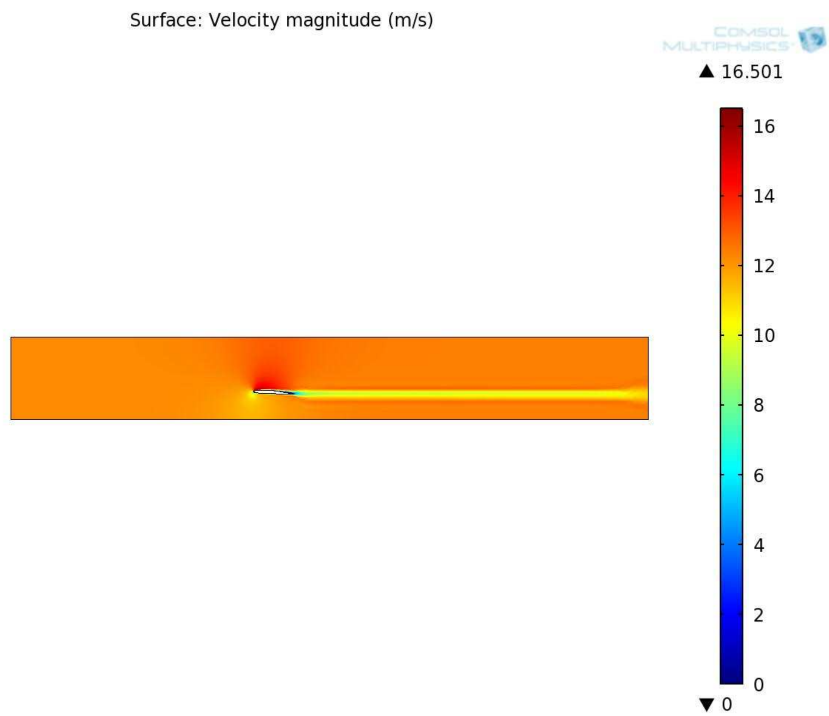

Figure 17 - COMSOL for airfoil at 3.6 deg.

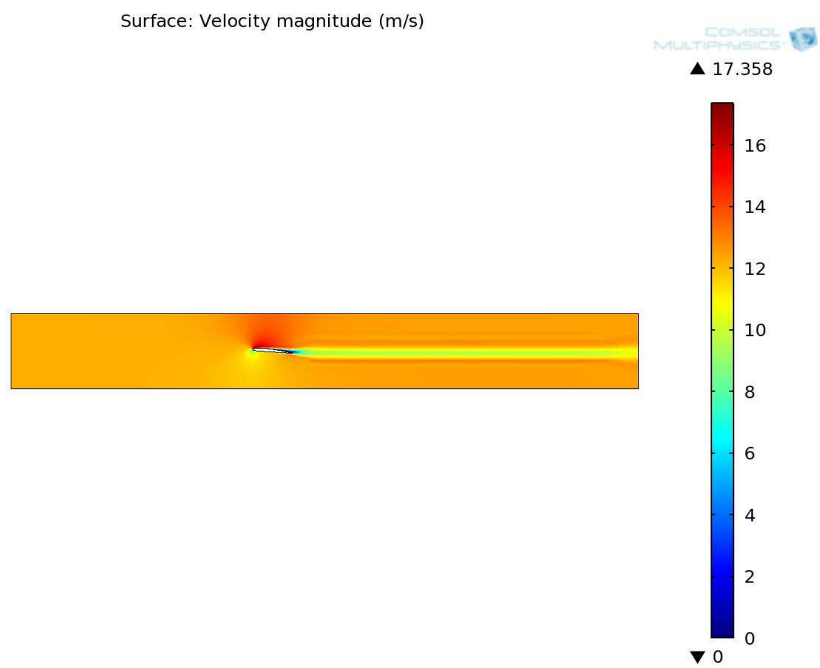

Figure 18 - COMSOL for airfoil at 5.4 deg.

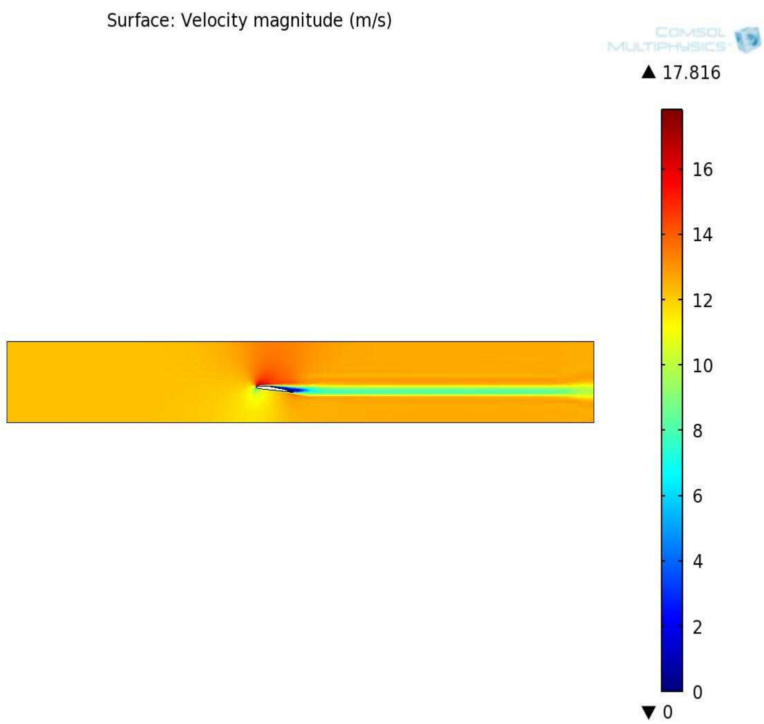

Figure 19 - COMSOL for airfoil at 7.2 deg.

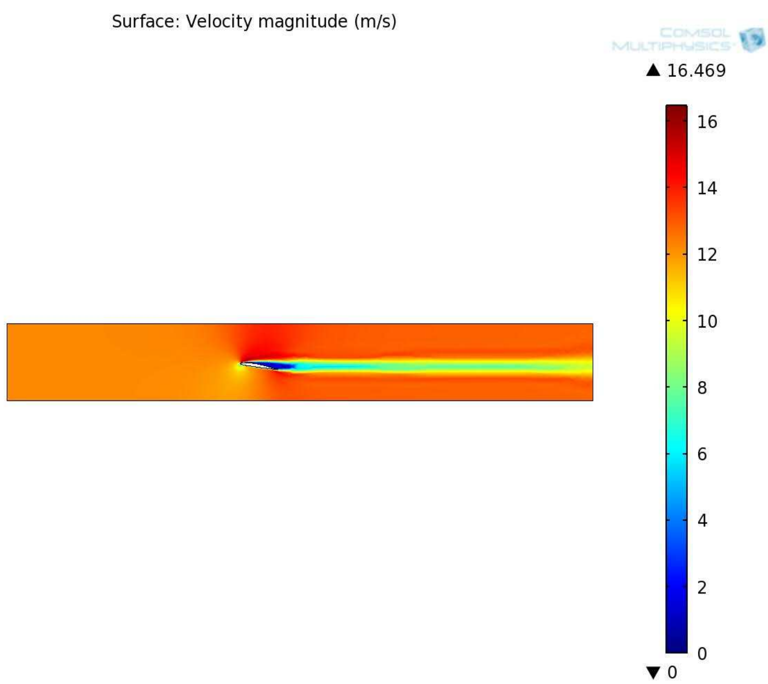

Figure 20 - COMSOL for airfoil at 9.0 deg.

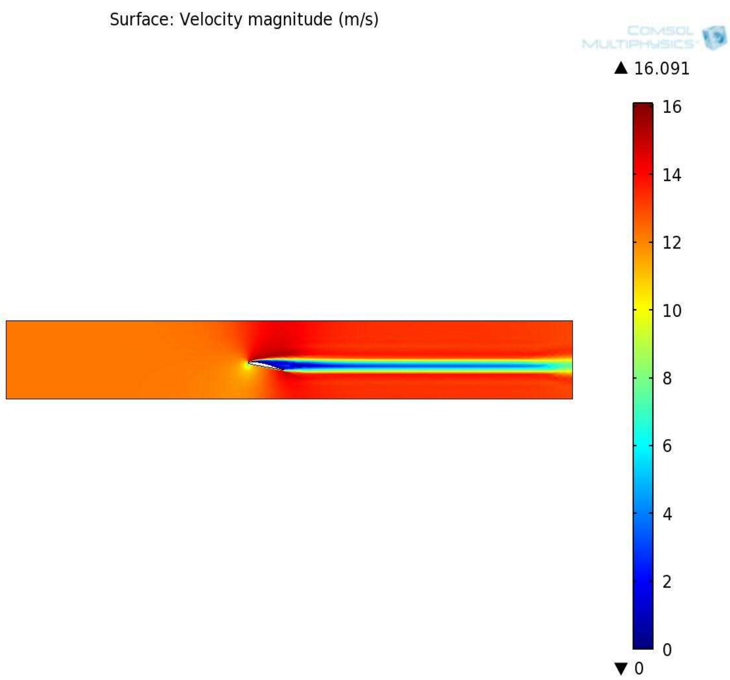

Figure 21 - COMSOL for airfoil at 10.8 deg.

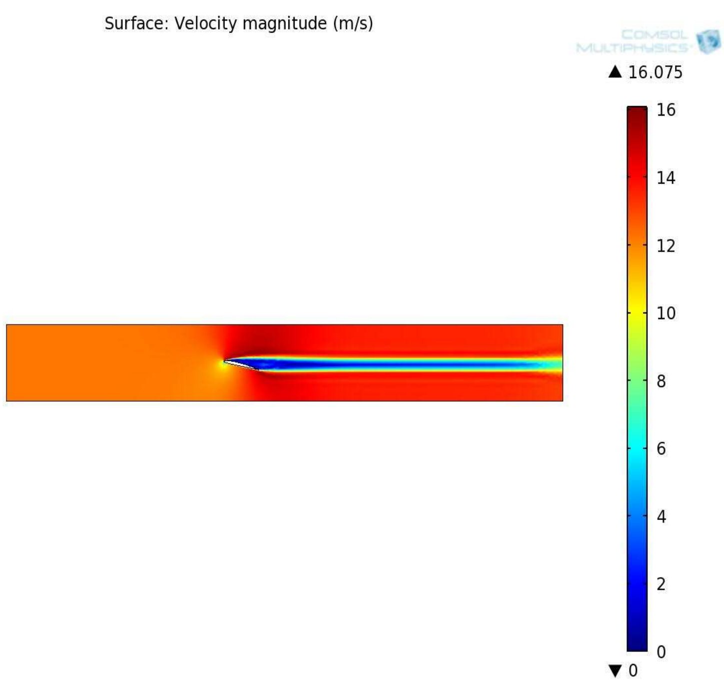

Figure 22 - COMSOL for airfoil at 12.8 deg.

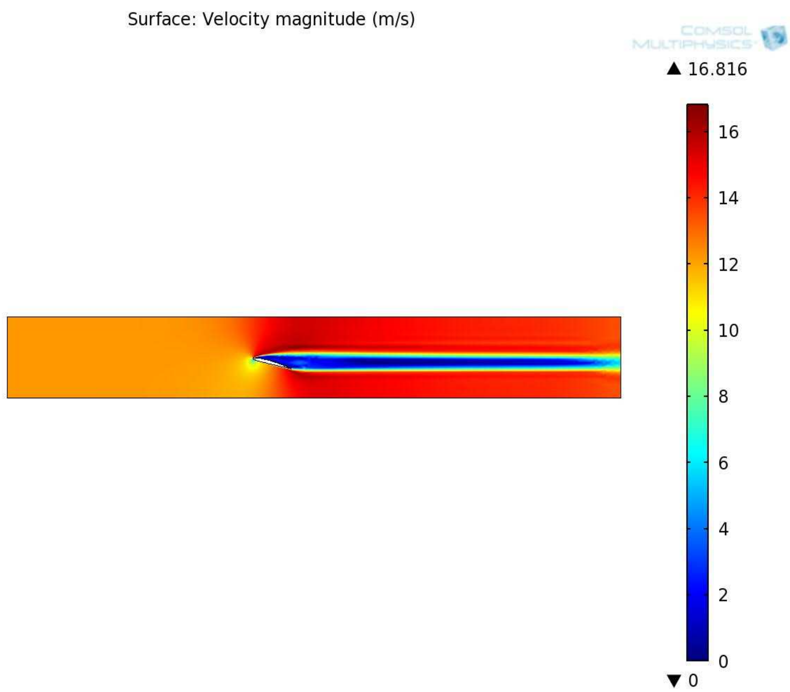

Figure 23 - COMSOL for airfoil at 14.4 deg.

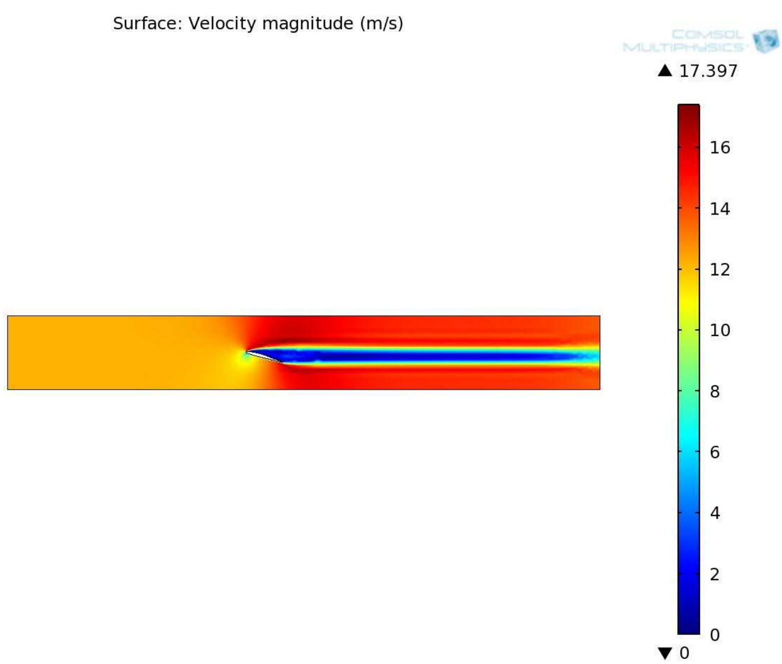

Figure 24 - COMSOL for airfoil at 16.2 deg.

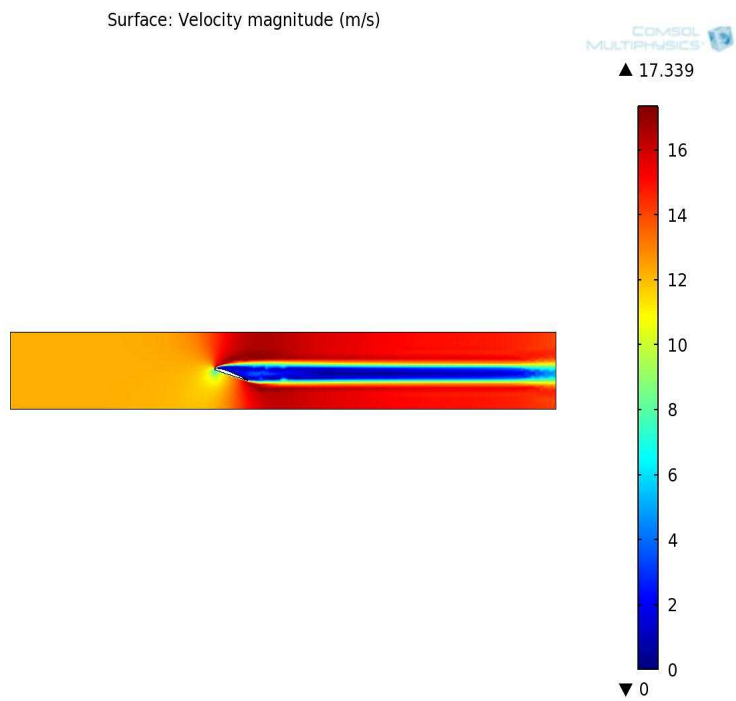

Figure 25 - COMSOL for airfoil at 18.0 deg.

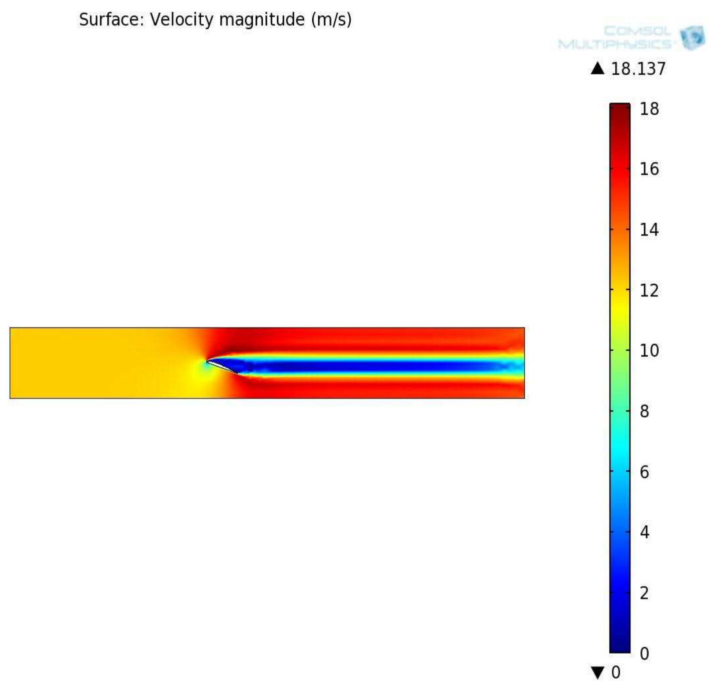

Figure 26 - COMSOL for airfoil at 19.8 deg.

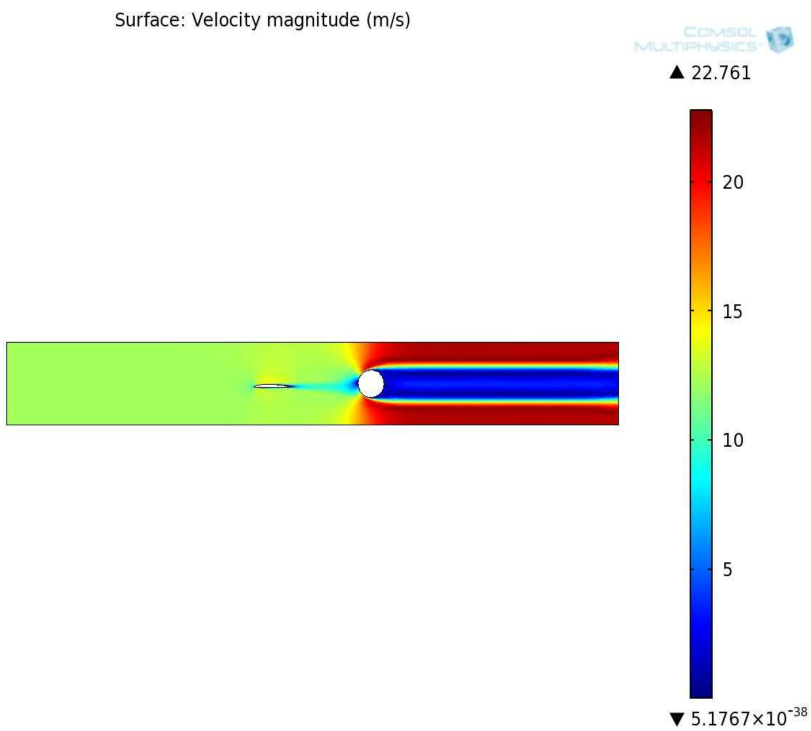

Figure 27 - COMSOL of airfoil in front of sphere

Appendix C – ProE

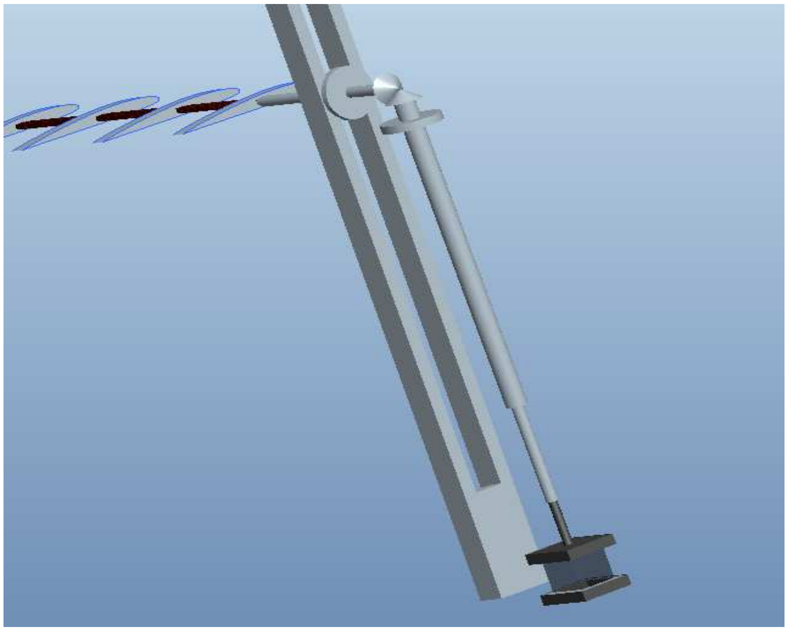

Figure 28 - ProE of gear shafts.

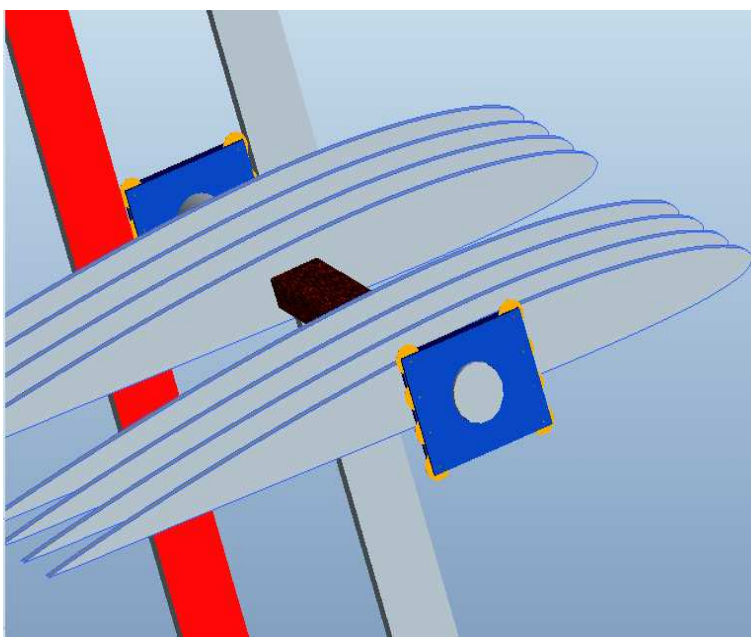

Figure 29 - ProE of side view for bearings and airfoils.