Wind Turbine Shroud Design

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Abstract: Continuing from last semester’s work, this semester’s project is about building and testing a wind turbine shroud that demonstrated the best Computational Fluid Dynamic results. Testing of the windmill shroud is conducted to justify the means of adding a shroud around a windmill to increase the speed of the airflow, thus generating more energy from the wind turbine blades. At a wind speed of 10 mph, the shrouded configuration resulted in a power increase over the non-shrouded configuration by a factor 2.4819. The cut-in speed of the shrouded configuration was 0.9 mph lower than that of the non-shrouded configuration. This means the shrouded configuration began generating power at slower wind speeds than the non-shrouded configuration. The power increase calculated by the CFD testing was 7.51% larger than the power increase achieved through physical testing, most likely due to the inaccuracies during construction of the shroud.

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**Introduction**

Renewable energy has become an important topic in recent years because of how fossil fuels affect the environment and how they’re being used faster than they are created. One major form of renewable energy is wind. Wind power is growing at a rate of 30% annually, so increasing the potential of the windmill is very important.

The current design of the windmill turbine has three large blades that spin slowly, which spins a shaft, which is connected to a gearbox to increase the rotational speed. Some torque is lost through the use of a gearbox. By increasing the rotational speed of the wind turbine, the gearbox and its torque losses can be eliminated from the design. Using higher density and smaller turbine blades allows for higher rotational speeds and a lower cut-in speed than the current low density three blade design. A venturi-like shroud will be placed around the turbine blades, increasing the velocity of the fluid where the pipe diameter decreases. This combination of a smaller, high-density blade and a venturi-like shroud allows for more power to be generated at any given wind speed and eliminates the need for a gearbox.

Last semester the design team researched how to increase the speed of the wind using a shroud covering the windmill turbine. Research was also conducted on how the actual windmill turbine would be built. Our research from the first semester concluded with the design shown in Figure 1.

![Figure 1: Windmill shroud from first semester’s research.](image)

The shroud is designed to imitate a Venturi pipe. The air flow would increase in the section where the pipe diameter decreases. The outlet of the shroud design has two functions. One is to vary the outlet diameter to control the pressure inside the shroud in order to increase the wind speed whenever it is low. The inner outlet diffuser ensures the air flow stays in
contact with the walls of the shroud upon exiting. A fin attached to the top of the shroud helps guide the windmill turbine to face the wind at all times.

Due to a two hundred and fifty dollar budget limit, the shroud design from last semester has changed so that the shroud can feasibly be built within the funds available. This semester’s purpose is to focus on designing and building only the shroud itself, and not a variable-diameter diffuser or the capability of rotation. We will do physical testing to compare the power output of a shrouded windmill and a non-shrouded windmill to see if using the shroud makes a noticeable power output difference. The computational fluid dynamics (CFD), using the software FLUENT, is continued from last semester to iterate a design that suits our needs. A prototype shroud will be designed, built, and tested. This shroud will be made of a wooden frame wrapped with Marmoleum (a type of vinyl). This report will cover the design, assembly, testing, and results phases of the project.

Design

The computational fluid dynamics done this semester was continued from last semester. Last semester’s CFD did not include a pressure jump condition that was needed to simulate the fan blades and get accurate results. This semester’s CFD work has included the pressure jump condition. To test the designs in FLUENT, a sketch was made in Pro Engineer of half of the shroud. Because the analysis done in FLUENT is axis symmetrical, only the top half of the shroud needed to be sketched. A few sketches were made to test different designs to find the best one.

The design had to meet certain criteria. One of the criteria was when the flow entered the shroud, the flow would need to increase in speed in the section where the shroud diameter is the smallest. The other criterion was that the flow should not separate from the walls upon exiting the shroud.

The initial phase of performing the computational fluid dynamics analysis last semester primarily consisted of learning how to use two programs, GAMBIT 2.3.16 and FLUENT 6.3.26. GAMBIT was used to create a 2-dimensional axisymmetric setup in order to develop a conformal mesh and state key boundary conditions as stated in Table 1. It was also used to further refine the mesh to validate and improve the CFD results within FLUENT. The drawing was exported from Pro-E as an IGES file that could be conveniently imported into GAMBIT. It was then exported as a MESH file into FLUENT. The main key requirement once the meshed drawing was imported into FLUENT was that the grid check passed and that a realistic volume was observed. Once this was achieved, the next task was making sure the boundary conditions transferred over successfully. Upon achieving this, a model solver had to be stated. The case
was treated as a pressure based, axisymmetric problem with green-gauss cell selected as the gradient option. The rest were left at default conditions. The remainder of the options such as formulation, time, velocity formulation and porous formulation were left at default settings as seen in Figure 2.

![Figure 2: Model Solver specifications](image)

The next requirement was to setup a viscous solver. After many consultations regarding which one to pick, the spalart-allmaras was decided to be the best option. The material fluid selected was air at default settings with a density of 1.225 kg/m³, viscosity of 1.79e-05 kg/m-s, and an operating pressure of 101325 Pascal. The next phase was stating the boundary condition variables. An inlet velocity of 10 mph, or 4.47m/s, was set and a pressure jump of -16.5 Pascal was used. This inlet velocity was chosen according to the standard operating conditions the wind turbine would be operating under. Since the testing would be conducted in Arlington, Texas, the area's average wind speed of 10 mph was used. The pressure jump was calculated theoretically using Betz' law and Bernoulli’s incompressible flow equation.

Defining the solution controls, initialization, and residual monitors was the next step. Figures 3, 4 and 5 display the specifications used. The problem was then set to iterate 1000 times. This resulted in a fairly accurate result, based off the convergence of the residual monitors. Once the 1000 iterations were completed, the process was done again with a refined mesh to compare results. After which the contour pressure and velocity vectors were graphed.

![Figure 3: Solution Controls Specifications](image)

![Figure 4: Solution Initialization Specifications](image)
The CFD performed last semester lacked an integral boundary condition of a pressure jump. Without the pressure jump, the readings acquired were irrelevant since it was merely airflow through and around a shroud without the simulation of a fan within the throat. Therefore, this semester the primary goal with regard to CFD was figuring out how to incorporate the pressure jump into the shroud. This goal was successfully achieved by being able to place the pressure jump at any point in the throat and specify its coefficient. Now came the second phase of finding a feasible and easy-to-manufacture design. The design came down to two iterations, the shroud with and without a diffuser. The final decision was made based on if it was feasible to include a diffuser and if the speed increase was enough to invest in. Based on the results acquired from CFD, it seemed unnecessary to include the diffuser since the benefits were not worthy enough.

As seen in the figures below, it is apparent in the shroud without the diffuser that there is a significant increase in wind velocity from 4.47 m/s to 6.2 m/s. Whereas, in the shroud with the diffuser there isn’t. In fact however, there is a better outflow due to the diffuser, which is very desirable since the faster the air exits, the faster it enters into the shroud.
Figure 8: Zoom-in of Mesh

Figure 9: Boundary conditions

<table>
<thead>
<tr>
<th>Location</th>
<th>Entity</th>
<th>Boundary Type</th>
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<tbody>
<tr>
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<td>Inlet Velocity</td>
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<tr>
<td>Right Edge</td>
<td>Outlet</td>
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</tr>
<tr>
<td>Top Edge</td>
<td>Top</td>
<td>Outflow</td>
</tr>
<tr>
<td>Bottom Edge</td>
<td>Axis</td>
<td>Axis</td>
</tr>
<tr>
<td>Turbine</td>
<td>Shroud</td>
<td>Wall</td>
</tr>
</tbody>
</table>

Table 1: Boundary conditions used within Gambit
The final dimensions of the shroud that was assembled and used for CFD are given below:

![Dimensioned drawing of the final design](image1)

Figure 10: Dimensioned drawing of the final design

Throughout the project there have been several design iterations of the shroud and the various components of the wind turbine. However, many of these designs were either meant for manufacturing processes that were out of our budget range, or were impractical. So a final 3D CAD model was made for our wooden skeleton design.

![3D CAD model of the final design](image2)

Figure 11: 3D CAD model of the final design
Fabrication & Assembly

In this section the fabrication of the shroud’s components and its assembly will be described step by step. The process can be broken down into three major steps; the construction of the shroud frame, wrapping the frame in a Marmoleum skin, and mounting the generator and blades within the shroud. The first step, building a frame for the shroud out of wood, was designed to hold the shape of the shroud as well as to act as a support for mounting the generator and blades. This frame consisted of two concentric rings joined by 1”x 4” wooden runners. Along these runners, various supporting pieces were attached to increase the strength of the structure.

The rings, which were cut from 5/8” thick plywood, were traced out using a custom made compass and cut out with a jigsaw. The outlet diameter was larger than could be cut from a standard 4 foot wide piece of plywood, so it was cut in quarters and later attached using metal plates. Figure 12 shows one of the quarters of the outlet diameter being cut from plywood.

The runners, which joined the inlet and outlet rings, were cut from 1”x4” pieces of pine. These were done in two pieces to match the profile and angles of the shroud. These pieces were attached using metal plates and the overall runner was attached to the rings using right angle metal brackets. Six of these runners were used and spaced 60° apart. When attaching
both ends of the shroud to the runners, a method for assuring their concentricity was utilized. A string was tied across the inlet ring and another string was hung from the center. This string was then matched to the center of the outlet ring.

To increase the strength of the structure, additional supporting pieces were attached on the sides of the runners at 45° to both the inlet and outlet rings. In addition to this, an additional two rings were added near the center of the shroud. These rings both increased the strength of the frame as well as served as attachment points for the Marmoleum skin. One was placed at the center of mass of the shroud and the other was placed about 1.5 feet away from the first. This made sure that the skeleton did not twist or bend once the windmill and generator were placed inside the shroud. Also, these rings would be where the pole or mounting structure may be attached.
The Marmoleum skin of the shroud was attached using drywall screws. Each sheet was screwed in along the sides of the rings and all the way along the length of the runners. The sheets were cut to the approximate shape and size of each section and then screwed into place. Once this was done, the sheets were cut flush against the wood. In order to shape the Marmoleum into a smooth round surface, long screws were driven through the sheet into the rings of the frame. These screws acted as ties to pull the material into a tight smooth shape. Tape was used to smooth the joint locations where the different sheets met.
After the inside of the shroud was covered, the generator and windmill blades were installed. The blades were purchased online and came with a Lexan hub and screws to attach the blades to the hub. Each blade is 18 inches in length and 3 inches wide. The hub is 6 inches in diameter. Each blade was placed on the hub for a total of 6 blades. The total diameter is 39 inches. Black electrical tape was used to cover up manufacturing holes near the end of the blades.

The DC-540 Low Wind Permanent Magnet Alternator from WindBlue Power is the alternator being used, and was attached to the hub and blades.
The generator, two light bulbs, and two multimeters were wired together to form a circuit for taking voltage and amperage readings. This setup will be further explained in the testing section of this report. To mount the blades and generator within the shroud it was essential that they be placed at the appropriate location, in the center, and on a fully rigid structure. The center was found using a piece string tied to the center of strings running across the diameter of each ring, creating a cord along the center axis of the overall shroud. The shroud was then placed upright and a 2”x4” was attached at the desired location. The 2”x4” position was adjusted using a standard bubble level.

Due to the use of low precision equipment and tolerance stack up from low grade materials, there will be discrepancies between the CFD results and the results of testing. The primary source of discrepancy will be found from the Marmoleum skin. When covering the shroud, it was very difficult to remove all of the bubbles and creases in the Marmoleum. It was a fairly difficult material to work with as it was not intended for this type of application. It lacked in the appropriate balance of rigidity and formability. This will create an irregular surface around and inside the shroud. Another discrepancy is that the inlet and outlet rings should have
a rounded surface rather than a flat surface. The only reason that we are unable to fix this is budgetary constraints.

Testing

The end goal of this project is to compare the power generation of the non-shrouded turbine configuration with the shrouded turbine configuration in a real world environment. In order to do so, each configuration will need to be tested in order to get the measurements needed to calculate the power produced by the alternator at various wind speeds.

The ideal environment to test the power output of a wind turbine is a space where the speed and direction of the wind are as consistent as possible. The wind speeds should vary from 0 mph to at least the average wind speed in the area the turbine will operate in, which in the case of Arlington, Texas, is 10 mph. This range of wind speeds allows for the opportunity to observe the cut-in speed, which is the wind speed at which the turbine begins to spin with usable power generation, and to observe how the turbine and generator perform at standard operating conditions. The turbine should ideally be faced exactly into the wind so that the energy harvested from the wind can be maximized.

The values that will be measured and recorded are voltage, current, and wind speed. The alternator used produces and outputs alternating current (AC), but also has a built in rectifier that converts the AC to direct current (DC) output. The DC outputs were hooked in series to two 14 volt, 4.6 Watt light bulbs that acted as a load to get usable current and voltage readings. One multimeter was added in series to measure the current in the circuit, and another multimeter was added in parallel to the alternator to measure the voltage. These two measurements are used to obtain values for power with the use of the following equation:

\[ P = I \times V \]

Where: 
- \( P \) = Power (Watts)
- \( I \) = Current (Amperes)
- \( V \) = Voltage (Volts)

The wind speed was measured using a handheld anemometer, which was kept facing in the direction the wind turbine was facing. These three measurements are used to create a Power vs Wind Speed plot for each configuration, which can then be analyzed and compared.

The first test conducted was for the non-shrouded configuration. The turbine blades and hub assembly were mounted onto the alternator. This assembly was then mounted onto an 8 foot long, 2” by 4” wooden post. The alternator mounting holes on the wood were measured and drilled, and the alternator was secured to the wood using two bolts.
Figure 23: The blades and alternator mounted onto the wooden piece
The alternator was then hooked into the circuit as mentioned above. The testing site was in a fairly open portion of a neighborhood which provided consistent winds at a variety of wind speeds. The wooden post was held upright into the wind, while a video camera recorded the screens of the anemometer and the two multimeters, providing us with simultaneous current, voltage, and wind speed readings. This was done until a sufficient amount of data was recorded for various wind speeds. The wind speeds ranged from 0 mph to 17.5 mph and were consistent enough to provide good data. A string was attached to the post to show the direction of the wind, so that the turbine could be manually turned into the wind constantly.

![Figure 24: A snapshot of the video recording the testing data readings for the non-shrouded configuration. The light bulbs pictured here are the ones being powered by the alternator.](image)

The second test conducted was for the shrouded configuration. The alternator and blade assembly were removed from the wooden post and installed onto the shroud. The wires from the alternator were secured to the alternator mounting beam, fed through a hole made through the walls of the shroud, and finally attached to the testing equipment. The shroud and testing equipment were moved to the same testing site as the first test. Ideally, the shroud should be mounted at least 8 or 10 feet high into the air with little obstruction from the mounting assembly, and should be able to freely rotate into the direction of the wind. Because the shroud is very large and heavy, it was not feasible to mount it on a post or pole as was done for the non-shrouded configuration. Instead the shroud was placed about two feet high onto a table. The inlet was elevated with wooden blocks so it did not slant downward. The shroud could only be pointed in one direction, so it was pointed in the direction that the majority of the wind was blowing at that point in time. This is not the ideal mounting setup to test the shroud, but we had a fairly good representation of the behavior of the shroud.
Figure 25: The shroud with the blades and alternator mounted, along with the wiring attached to the testing equipment.

Figure 26: The data acquisition setup for the shrouded configuration test.
The blades were allowed to rotate and the video camera recorded the anemometer and multimeter readings. The wind speeds ranged from 0 mph to 12.9 mph and were consistent enough for good data measurements. It is important to note that the anemometer was reading the environment wind speeds, and not the speed of air inside the shroud.

![Figure 27: A snapshot of the video recording the testing data readings for the shrouded configuration.](image)

Results

The data acquisition videos were reviewed in order to write down the current and voltage conditions for various wind speeds. The anemometer used had about a one second delay in displaying its readings. So in order to retrieve the voltage and current numbers at a certain wind speed, the anemometer reading needed to be steady (unchanging) for at least a couple seconds. This is why consistent wind speeds were needed for testing. The data points used for analysis were only taken from steady wind speed readings. The current, voltage, and wind speed data were collected into an Excel spreadsheet. The data collected for each configuration are as shown below:
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<th>Wind Speed (mph)</th>
<th>Voltage (Volts)</th>
<th>Current (Amps)</th>
<th>Power (Watts)</th>
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<tbody>
<tr>
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<td>1.0752</td>
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</tbody>
</table>

Table 2: Data collected for the non-shrouded configuration

Figure 28: Power vs Wind Speed for the non-shrouded configuration

The cut-in speed for the non-shrouded configuration was 7.5 mph.
The cut-in speed for the shrouded configuration was 6.6 mph, a 0.9 mph decrease from the non-shrouded configuration.
The data was then fit with a linear curve fit to be able to compare power output at any wind speed between the two configurations.

The R\textsuperscript{2} values for the shrouded and non-shrouded linear curve fit configurations are 0.9608 and 0.9858 respectively. This means the shrouded curve fit line is 96.08% accurate to its data points, and the non-shrouded curve fit is 98.58% accurate to its data points, both of which are good enough for using as a comparison to each other. It can be seen that the shrouded configuration did increase the power output for any given wind speed compared to the non-shrouded configuration.

The CFD results concluded that shroud speeded up the airflow from the environment to the blades from $V_{\infty} = 4.47 \text{ m/s}$ (10 mph) to $V = 6.2 \text{ m/s}$ (13.869 mph). This results in velocity increase coefficient of:

$$V_{\text{increase CFD}} = \frac{V}{V_{\infty}} = \left( \frac{6.2 \text{ m/s}}{4.47 \text{ m/s}} \right) = 1.387$$

where $V_{\infty}$ is the environment air velocity and $V$ is the velocity of the air just before the turbine blades. Since power is proportional the cube of velocity, $P \sim V^3$, then the theoretical power increase coefficient from the CFD results is:

$$P_{\text{increase CFD}} = V^3 = 2.6683$$
To check how the CFD power increase compared to the physical testing power increase, the power output of the non-shrouded and shrouded configurations are compared at 10 mph (4.47 m/s). At 10 mph, using the linear curve-fit equations from above, the non-shrouded configuration produced 4.146 Watts and the shrouded configuration produced 10.29 Watts. So the power increase coefficient from the non-shrouded configuration to the shrouded configuration is:

\[ P_{\text{increase physical}} = \left( \frac{P_{\text{shroud}}}{P_{\text{non-shroud}}} \right) = \left( \frac{10.29 \text{ W}}{4.146 \text{ W}} \right) = 2.4819 \]

This physical testing increase is slightly below the CFD power increase.

The error of the CFD power increase compared to the physical testing power increase can be calculated by:

\[ \frac{P_{\text{increase CFD}} - P_{\text{increase physical}}}{P_{\text{increase physical}}} = \frac{(2.6683 - 2.4819)}{2.4819} = 0.0751 = 7.51\% \]

So the power increase calculated by the CFD testing is 7.51% larger than the power increase achieved through physical testing. This error is most likely due to the inaccuracies during construction of the shroud which were caused by tolerance stack up and the workability of the materials used.

**Conclusion**

The objective of this project was to design and build a shroud, in which a wind turbine will be placed inside of, in order to speed up the airflow and thus generate more power. Using computational fluid dynamics, many designs were tested, and a final design that fit our budget was created. The proposed design was constructed and tested, and then the results were compared to the test results of the non-shrouded blades.

At a wind speed of 10 mph, the shrouded configuration resulted in a power increase over the non-shrouded configuration by a factor 2.4819. This proves that a shrouded wind turbine, when designed properly, does produce more power than a non-shrouded wind turbine using the same diameter blades and same wind speed. The cut-in speed of the shrouded configuration was 0.9 mph lower than that of the non-shrouded configuration. This means the shrouded configuration began generating power at slower wind speeds than the non-shrouded configuration. The power increase calculated by the CFD testing was 7.51% larger than the power increase achieved through physical testing, most likely due to the inaccuracies during construction of the shroud. If one has the right materials and tools available, a more ideal and precise design could be built with even larger power increases, so this idea should definitely be pursued and more fully researched in the future.
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