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In the Wind:

From Tunnel to Turbine

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Abstract- A country or region where energy production is based on imported coal or oil can become more self-sufficient by using alternatives such as wind power. Horizontal axis wind turbines are the most common wind turbine design available and are typically seen with three blades. These projects observed the effect of blade number on the start-up wind velocities of wind turbines. Models were drawn using SolidWorks and generated by a stereolithography machine. The models were observed in a wind tunnel by using the flow visualization methods of smoke and Schlieren photography. The wind tunnel was constructed to have at least double the test section area of the current fluid mechanics laboratory wind tunnel and was able to achieve a wind velocity range from 5mph to 25mph. This paper is a summary of 3 projects performed by the authors at USM.

Keywords—wind, wind tunnel, wind turbine, turbine design, turbine modeling, wind tunnel modeling, Betz's Law.

I. INTRODUCTION

The 1990's saw a strong resurgence in the worldwide wind energy industry, with capacity increasing over five-fold and the shift toward megawatt-sized wind turbines. The trend has continued into the 21st century with increased government policies focused on developing domestic sustainable energy supplies and reducing pollutant emissions. A wind turbine is a machine that converts the power of wind into electricity. The conversion process uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting in the production of mechanical power that is then transformed into electricity by a generator. The most common wind turbine design is the horizontal axis wind turbine (HAWT) in which the main rotor is connected to a horizontal shaft and electrical generator at the top of a tower, and must be pointed into the wind. HAWT designs consist of one or more blades. One HAWT design consists of a main rotor covered by a shroud that allows the capture of more wind energy while taking up less space than a traditional turbine. Such a design is known as a shrouded wind turbine and is constructed so that different airflows create a rapid-mixing vortex.

A wind turbine model is created and tested in a wind tunnel. Designs are better understood and improved upon based on the performance of the model in the wind tunnel. A wind tunnel may be open and draw air from outside the tunnel into the test section then release it back outside or alternatively, the tunnel may be closed with the air re-circulating through it. The flow conditions in the tunnel can be controlled in order to not only test the forces on, and performance of, various object designs for research, but also for the demonstration of aerodynamic principles in the classroom.

During wind tunnel testing, it is important to determine the air flow patterns and flow separation over a model. Since air is transparent, the flow patterns are invisible without flow visualization methods such as surface flow visualization, particle tracer visualization, and optical visualization. Surface flow visualization utilizes oil or tufts applied to the surface of the model. As the air flows over the model, the flow patterns can be observed. The use of smoke in order to observe the flow of air over a model is an application of particle tracer visualization. Schlieren photography is a method of optical visualization in which the varying density of the air results in a set of lighter and darker patches corresponding to positive and negative density gradients. These methods can be implemented to obtain qualitative information on the airflow around and over a model in order to analyze its performance.

The turbine, wind tunnel, and shroud have been designed and visualized (statically, dynamically, and in animation) by utilizing Solid Works for both the structural and fluid sections of the design.

II. OBJECTIVE

The objective of this project included building a wind tunnel that can be used to observe the performance of various horizontal axis wind turbine models using particle and optical flow visualization methods.

The wind tunnel is used to observe the performance of designs through models mounted in the testing section. The performance characteristic to be observed is the wind velocity at which the model wind turbine begins to rotate. This is an important characteristic because wind turbines that start generating power at lower wind speeds are useful in order to expand the potential for wind power in more geographical areas. The number of blades on each wind turbine model is varied in order to observe the effect that blade number has on the start-up wind velocity. The effect of a shroud on start-up wind velocity is determined. The models tested were: two and three blade turbines; multi-blade turbines, shroud and mixer-ejector designs.

The flow visualization methods that were used are smoke and Schlieren photography. The smoke method is a classic method in which smoke particles travel along the air in streamlines. The Schlieren photography method is more difficult to implement. It uses the change in air density to observe the air flow around the mounted model.

An easy to transport and store wind tunnel was built at a fraction of the cost of the current laboratory wind tunnel. It will be for the purpose of instruction and simple research in the fluid mechanics laboratory. This wind tunnel is used in these projects to observe the start-up wind velocity of shrouded, two-, three-, and multi-bladed horizontal axis wind turbine models. Flow patterns over the models will be observed by using smoke, tuft, and Schlieren photography methods. These observations are used to verify the Solid Works modeling on each of the designs.

A. The Wind Tunnel

A wind tunnel [1] consists of several distinct sections or stages. Moving in the direction of the airflow, the first section is the air straightener. The air straightener is a honeycomb screen that redirects turbulent air from its various entry vectors to a vector roughly in line with the long axis of the wind tunnel, thus “straightening” it. The next section is the contraction cone, named for its shape and purpose; it is meant to contract the low velocity air entering the tunnel into a smaller volume of high velocity air with laminar flow. The test section is the chamber in which the wind turbine models will be placed. It is made of transparent materials to allow observation and data acquisition. Finally, the diffuser section is after the test section. The diffuser performs in an opposite fashion to the contraction cone. It widens out from the test chamber to the fan housing allowing the high velocity air to transition to a larger volume and lower velocity. By controlling this transition any turbulence that might create drag by back flowing into the test chamber can be diffused [2].

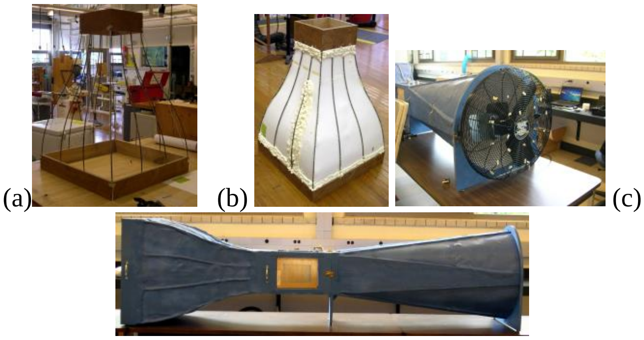


Fig. 1a. Twelve symmetrical steel rods shape the contraction cone and keep the small frame centered.

Fig.1b. The spray foam is used to fill in the gaps between the rods and the poster board.

Fig. 1c. The fan and wind tunnel painted and fully assembled.

The first significant challenge in the visualization and design by Solid Works is shown in Figure 2.

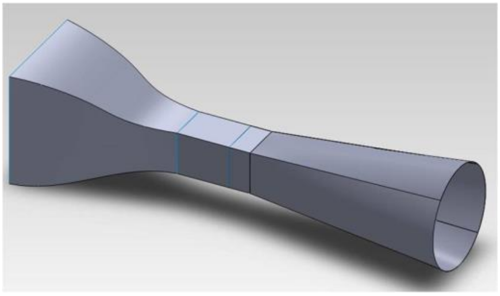


Figure 2. Solid Works design

Accommodating the thickness of material without altering the interior dimensions of the wind tunnel required careful planning and a critical eye making certain everything remained in correct proportion. The simulation of the design in FloExpress (Solid Works) was the next essential step as shown in Figure 2.

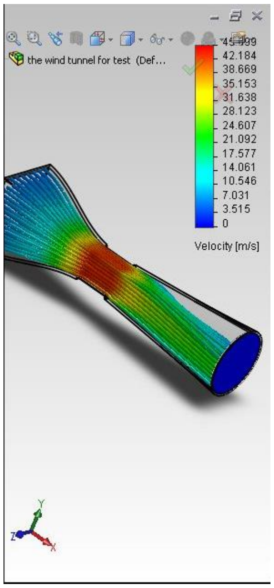


Figure 3. FloExpress (Solid Works) flow simulation

B. The Turbine Blades and the Mixer Ejector

The purpose of this portion of the project was to:

1. Design and test the effects of multi-blade turbines for output vs wind velocity;

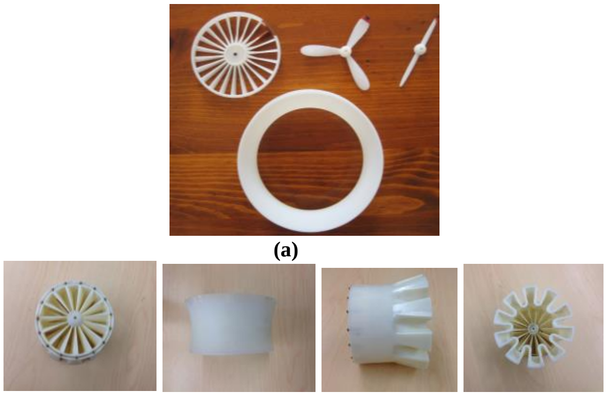
2. Observe the Venturi effect due to Mixer/Ejector Technology being introduced to the design of wind turbines.

3..The specific objectives of this project also included:

- Create a small scale wind turbine with Mixer/Ejector Technology based off FloDesigns’s model in 3D

space by using SolidWorks and printed with stereolithography.
- Test the models in the USM fluid mechanics laboratory wind tunnel.
- Test the models in SolidWorks Flow Simulation for velocity and observe the Venturi effect.

This project was conducted in three stages, after the large wind tunnel design and fabrication. During the first stage the models for various wind turbine rotor designs were created. The multi-bladed wind turbine rotor model was provided by a Massachusetts company (FloDesign Wind Turbines, FDWT) that specializes in wind turbine design. The design was modeled by students for a senior project for the company using SolidWorks CAD software. A physical model of the **multi-bladed rotor** was created using the stereolithography machine at the University of Southern Maine. The 3-D printer at USM is an OBJet 30, which uses up to seven different materials including transparent and high-temperature photopolymers. It prints material at 28 micro-meters per layer to create a realistic model for testing**.** Other designs for wind turbine rotors included **two- and three-bladed rotors**. The SolidWorks model of the three-bladed rotor was provided by Langley Research Center. The models were either resized or created with a diameter of 4 inches. A shroud was created in SolidWorks to surround the rotors. The two-bladed rotor, three-bladed rotor, and shroud were also turned into physical objects by the stereothiography machine as seen in figure 4a. Larger models were printed as shown in figure 4b. The machine would run for approximately a day and then the models would have to sit for a period of time in a bath with a chemical to clean the models before use.


(a)

Mixer with Rotors **(b)** & Ejector

Figure 4. Initial stereolithography model turbines (a) 3", (b) 6"

The second stage of the project included testing the physical models in the wind tunnel located in the fluid dynamics laboratory in John Mitchell Center. The models were to be tested using smoke and schlieren photography methods. Video was also to be taken during testing in order for review and for later analysis on Videopoint software to track the rotations per minute of each rotor. The wind tunnel was shown in figure 1. A small cart was developed, shown in figure 5, in order to mount the rotor models inside the wind tunnel. The cart was connected to the drag gauge to hold it in place. The models were placed in the wind tunnel one-by-one. They would be run at 500 feet per minute (FPM) with video taken first for Videopoint analysis. Schlieren photography was used in a later project due to its complexity.

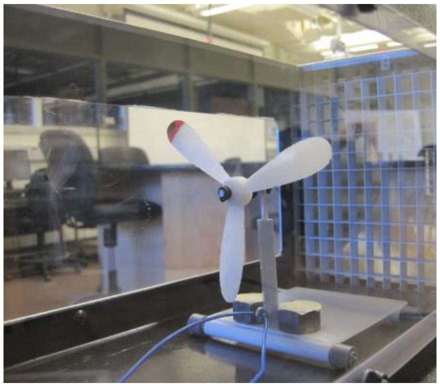


Figure 5. Turbine cart for wind tunnel

The third stage of the project consisted of testing the SolidWorks models of the rotors and shroud using SolidWorks Flow Simulation. The rotor models were placed one-by-one into a simulation in which the air speed was set at 2.24 meters per second (m/s) or 5 miles per hour (MPH). The computers were left to process for a considerable amount of time, either to the finish or for an hour depending on which came first. During the simulation point goals were placed in order to get an average velocity in the rotor plane. Images were also captured of the flow variation during the simulation. After the completion, flow trajectories were inserted in order to view the flow over the rotor models. After simulation of the rotor models was completed, the simulation of them with the shroud was conducted in the same manner as mentioned above. Results were then compared. Some of the results are shown below.

III. RESULTS AND OBSERVATIONS

A. Rotor Motion

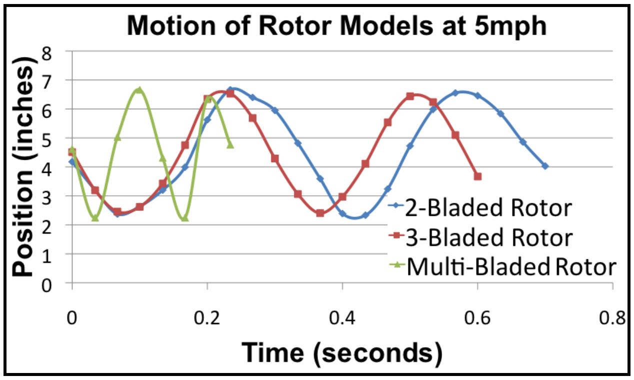


Figure 6. Motion obtained through Videopoint analysis.

From this data the 2-,3-,and multi-bladed rotor rotate at 200rpm, 225rpm, and 448 rpm respectively.

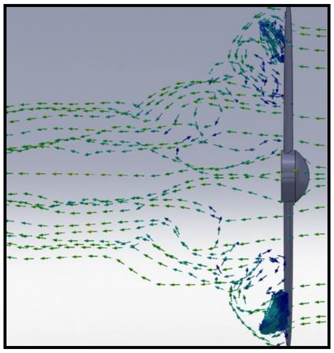


Figure 7. Airflow on 2-bladed rotor. Volumetric flow rate of 52.4 CFM

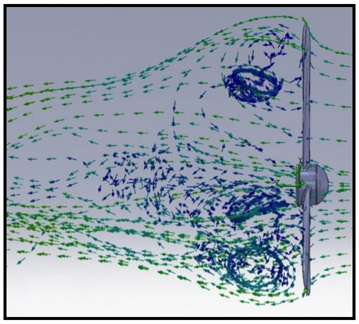


Figure 8. Airflow on 3-bladed rotor. Volumetric flow rate of 58.23 CFM

<u>Note the turbulence</u>

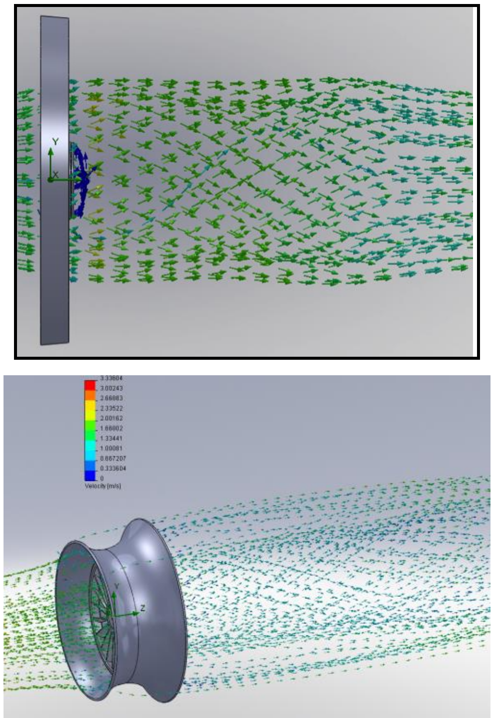
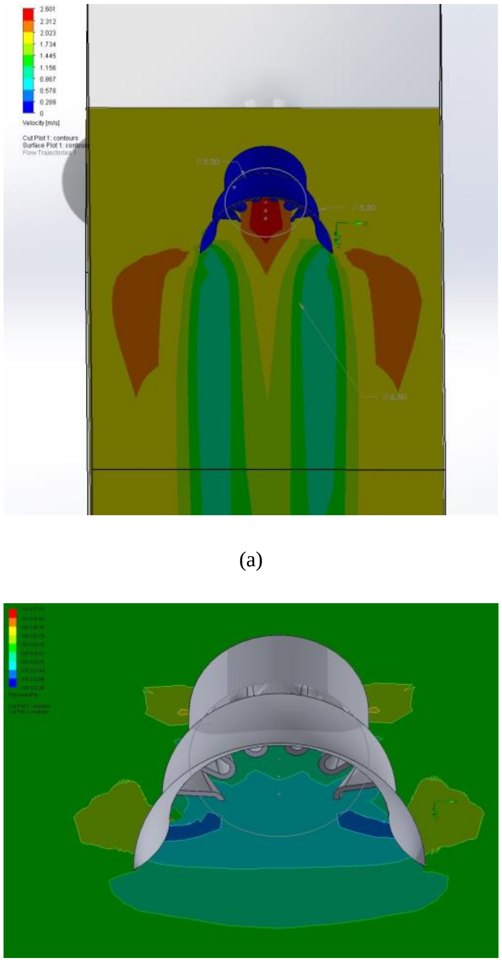


Figure 9. (a)Airflow on multi-bladed rotor. Volumetric flow of 72.10 CFM. The flow is collimated and there is rotation. There is <u>no turbulence</u> driven by wing tip vortices as in the 2- and 3-bladed rotor model simulations. (b) Note the shrouded multi-blade turbine flow convergence.



(a)

(b)

Figure 10. The velocity increase can be seen (a) as well as the pressure decrease (b)

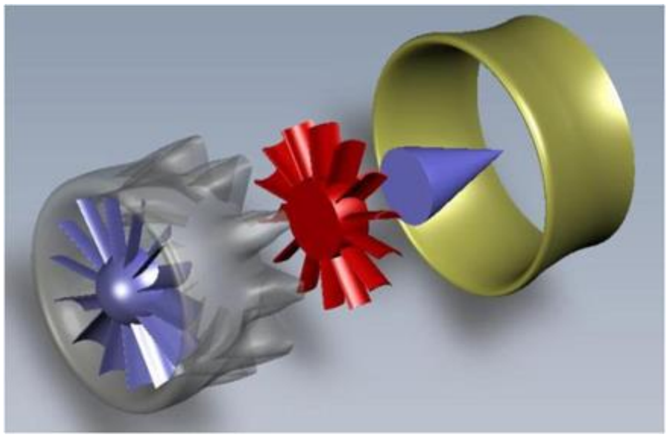


Figure 11. Model of FloDesign Turbine in present form

IV. CONCLUSIONS

EFFICIENCY OF THE MODERN TURBINE:

Most modern wind turbines are rated by efficiency. The efficiency comes from the Betz Limit. Betz's law calculates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. It was published in 1919, by the German physicist Albert Betz. The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized "actuator disk" that extracts energy from the wind stream. According to Betz's law, no turbine can capture more than 16/27 (59.3 percent) of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient or power coefficient. Practical utility-scale wind turbines achieve at peak 75% to 80% of the Betz limit. The problem with this theory is that it does not apply to the most modern shrouded wind turbine designs. The calculation uses that cross-sectional area of a cylinder to replicate the swept area of the turning blades. It does not account for any air flow outside of that cross-sectional area that contributes to power generation. With the addition of a shroud there is certainly more airflow that should be accounted for. It is easy to see that a shrouded turbine will be more efficient than modern three bladed turbines by simply comparing velocity ratios of (V_2/V_1). Ratios of 1.2X ambient airflow with the mixer were achieved and 1.5X ambient with the ejector. FloDesign claims a 1.8X output velocity over ambient air velocity. The ratio for all unshrouded wind turbines is less than 1X ambient. The calculations for the Betz limit as a result of the SolidWorks simulations support the claims that it can be “beaten” by adding more blades. The Betz limit is not appropriate to be used when the design is not within the correct parameters of 0.5 for the power coefficient. Also if the velocity at the rotor plane were to be increasing then the Betz limit is found null and void because as a condition it assumes that the velocity slows down as it enters through the rotor plane. As seen in the results, the airflow is increasing with the addition of a shroud to the rotor and thus the velocity is increasing in accordance.

The results from the Videopoint analysis were not all unexpected. From observation of the smoke tests in the wind tunnel the 3-blade rotor turned very slowly compared to the multi-bladed rotor. The 2-bladed rotor appeared to rotate faster and slower than the 3-bladed rotor depending on its position on the mounting cart. This would occur because of the airfoil and blade shape of the 2-bladed rotor as compared to the 3-bladed rotor. The 2-bladed rotor had blades that were rather slender and could cut through the air faster. However, at other times the small cross section of the blades did not allow much wind to be captured and it would turn more slowly than the 3-bladed rotor (actually, the resolved rotational force is greater with more blades). The multi-bladed rotor seemed to prove that a well designed blade and multiple blades can produce the effect of adding more lift and thus more rotation. This would be desired in the application of low wind speeds where more power can be generated at a lower speed because less wind volume velocity is being used to turn the rotor faster than the 2- or 3-bladed rotor designs.

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