Airflow Velocity Measurements: A Project-Based Learning Experience

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Abstract: This paper describes the involvement of undergraduate students in a multidisciplinary team-based research project between three engineering programs. The paper focuses on the contribution of a subgroup of mechanical engineering students working on the airflow measurements around a single fan, triple fans, and a small-scale wind turbine. The paper outlines the process undertaken by students to design and perform the experiments and reflects on the challenges and lessons learned. Three different experiments were conducted to measure the airflow around the fans and wind turbine with the aim of defining a “No Fly Zone” for drones. The single fan setup analyzes the flow created by one fan, as this was the preliminary test for the computer engineering team to design a path-planning for drones used for inspection. The more complicated three-fan setup was designed to experimentally analyze the flight capabilities of drones flying in a turbulent region where the magnitude of airflow is constantly changing. This experiment mimics turbulent regions that would take place between several wind turbines as they are rotating. The final experiment dealt with the measurements of airflow surrounding a small-scale horizontal axis wind turbine in a Lab environment as it is driven by wind generated from a blower. The blower for this setup is simulated using a large floor-drying fan outside the testing area. The air velocity for the three experiments was measured in a three-dimensional grid-based fashion and then analyzed. The collected data will be shared with the drone path-planning students from electrical and computer engineering to develop a robust control system for drones flying through the airflow generated from single and triple fans and the small-scale horizontal axis wind turbine. Finally, the challenges and lessons learned from each experiment are presented from the students’ perspectives.

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INTRODUCTION

Various techniques can be used to measure airflow around small wind turbines. Hot-wire anemometry, Particle Image Velocimetry, Ultrasonic anemometry, and pressure-based anemometry are the most used techniques. The choice of technique depends on the size of the wind turbine, the precision required, and the available resources. Mendoza et al. (2019) used hot-wire anemometry to measure the airflow around a small wind turbine with a diameter of 1.8 meters and provide insights into the performance and flow characteristics of a Savonius rotor, which can be useful for designing and optimizing small wind turbines for various applications. Shrestha et al. (2017) used Particle Image Velocimetry (PIV) to measure the airflow around a small horizontal axis wind turbine (HAWT) with a rotor diameter of 0.8 m in a wind tunnel and revealed that the performance of the HAWT was strongly influenced by the wind speed and angle of attack. Recently, Wang et al. (2020) used ultrasonic anemometry to measure the airflow around a small wind turbine with a diameter of 1.8 meters and revealed that the maximum power coefficient and torque coefficient are observed at a wind speed of around 10 m/s and an optimum angle of attack of 5 degrees. In addition, Wang et al. (2019) used pressure-based anemometry to measure the airflow around a small wind turbine with a diameter of 1.2 meters. The study showed that the wake's velocity deficit and turbulence intensity increase with the increase in downstream distance, and the maximum velocity deficit and turbulence intensity were observed at a distance of 3-5D (where D is the rotor diameter) downstream.

Over the past year, UVU has hosted a multi-faceted research project which aims at developing an autonomous inspection technique for wind turbines using drones and developing a predictive maintenance model of damaged wind turbine blades based on reliability analysis. This project involves electrical, computer, and mechanical engineering undergraduate students working on several aspects of the project. The electrical and computer engineering teams have been designing path-panning algorithms for a quadcopter drone to inspect wind turbines. This drone will fly autonomously, identify the turbine blades, and record any damage identified on the blade surface. Initial work has been accomplished on these aspects of the drone as described by Branden Pinney et al. (2022).

To assist in the path-planning of the drone, our group consisting of 3 students from the mechanical engineering team was tasked with the conduct of three different experiments to measure the airflow generated by a single fan, triple fans, and a small-scale wind turbine. These experiments were designed to test a small drone flight capability that the other teams were using for their path-planning tests. The objective of these experiments was to record the magnitude of wind velocity experienced at different areas in space for three different setups. The first setup analyzes the flow produced by a pedestal fan. This fan was expected to produce a conical-shaped air flow, expanding out from the center. The second setup involves three of these fans, spaced equally apart, forming an equilateral triangular shape, and pointing toward the centroid of the triangle. This setup was intended to create a turbulent flow region to test the stability of the small drone as it hovers in the vicinity of a fan. The final setup uses a small-scale wind turbine driven by a large fan to simulate the actual conditions this drone would be operating.

DESIGN OF THE EXPERIMENTS AND DATA COLLECTION

Our mentors asked our subgroup to design three different experiments to measure the airflow around a single fan, triple fans, and a small-scale wind turbine. We were lost at the beginning on what to do but after reading some articles and discussing with our mentors in more detail how we were going to do about the design of the experiments and what sort of measurement tools were needed to have reliable data and repeated experiments. We initially designed the simplest first experiment dealing with a single fan and showed our detailed design to our mentors for their approval. After several alterations to the initial design, we came up with the final design and started running some experiments. This first exercise gave us confidence in our collected data and in building our self-esteem to design the next experiments on our own. We went ahead and designed the other two experiments and presented the detailed designs and approach being adopted to measure the airflow velocity around the triple fans and the small-scale wind turbine. This has received a good appraisal from our mentors.

This work has been composed to explain the process our subgroup went through to perform these experiments, including the challenges encountered along the way. Each experimental method will be discussed with details on the setup and data recording process. The preliminary results will also be included to demonstrate the overall shape of the recorded airflow. Following the details of these experiments, the major challenges encountered in each experiment and the lessons learned are discussed in the following sections.

CASE 1: SINGLE FAN EXPERIMENT

This is the first experiment we conducted, and it took a long time to design the experiment by trying different layouts and collecting preliminary velocity measurements until we felt comfortable with having consistent data. So, we used the final layout for further measurements. We developed the experimental procedure defined as follows. A three-dimensional grid around the front side of a single pedestal fan was defined to a maximum distance of 3ft away in the principle X, Y, and Z directions. The X-direction was directed toward the left side of the fan and the Y-direction was defined to the front of the fan. We placed the fan at the origin of this grid, where the center of the hub was directly above the red dot as shown in Figure 1. We then established a plan for data points to be collected every 9 inches apart, and we laid out a two-dimensional X-Y grid on the floor using masking tape (see Figure 1). We specified five horizontal X-Y planes defined at different heights (Z-values associated with these planes were -12, -9, 0, 9, and 12 (inches), respectively) to record the airflow velocity. We placed the center of the fan to be in the plane at Z = 0 and the next two planes were set 9 inches away above and below the center plane, following the same distance definition. The last two planes were located 12 inches away from the middle plane as this was the edge of the flow pattern where the velocity becomes zero.

We used a handheld anemometer pointing toward the center of the fan at each data point to record the air velocity. This anemometer recorded the velocity in m/s. After several trials, we found out that the most difficult part of this experiment involved discovering how to keep a consistent height of the anemometer to record several data at the various XY planes. Several setups were experimented with, including taping some scrap wood to the base of the yardstick as support (see Figure 2). In addition, we used a wireless anemometer, which did not accurately record the lower velocity wind speeds.

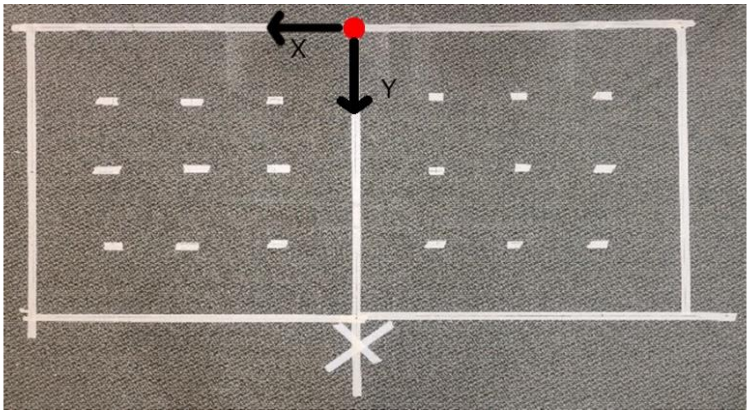

Figure 1: The x-y plane setup used for data collection.

Figure 2: Rudimentary wooden block set up to hold the anemometer.

To check the flow behavior for a single fan, we used MATLAB to plot the airspeed at various locations as shown in Figures 3 and 4. The measured velocity of this experiment successfully showed that the airflow creates a conical shape expanding outward at distances farther away from the fan center (see Figures 3 and 4). As expected, the highest magnitude air velocity was recorded along the centerline of the fan. Surface plots were created for the data at each Y-value in front of the fan showing the magnitude of the windspeed as it develops. Figure 3 illustrates the surface plot for the XZ plane located directly in front of the fan running at a low speed of 600 rpm. For ease of comparison, Figure 4 shows the surface plot for the plane 36 inches away from the centerline of the fan. This behavior assured us that our measurements are accurate enough to start the next experiments.

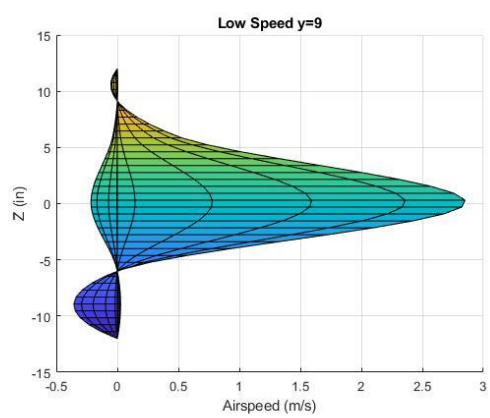

Figure 3: Low-speed surface plot at Y = 9 inches.

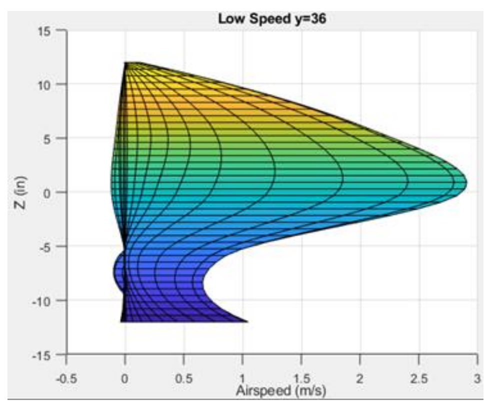

Figure 4: Low-speed surface plot at Y = 36 inches.

CASE 2: THREE-FAN EXPERIMENT

The experimental procedure for Case 2 was more complicated than Case 1 and presented more challenges to us as we must design the experiment in such a way that the three fans would form a triangular shape. We designed the grid to position the anemometer at each point for airflow measurements. We placed the three fans at the corners 6ft from its center to form an equilateral triangle. We made sure that all three fans were pointing toward the center of this triangle after which we set the three fans at a low speed of 600 rpm. Based on the obtained raw data from the first experiment, it was determined that a 9-inch spacing between the data points was too large to accurately represent the data. Thus, we decided to make measurements at every 6-inch spacing for this experiment. The representation of the intended XY grid is shown in Figure 5, where the red dots represent the fan locations, the blue dots represent the measurement locations, and the origin of the coordinate system is shown with green arrows.

Realizing the turbulent flow inside this triangle was expected to create flow in all directions caused by air coming from the three fans. Thus, we decided to analyze this field by recording the data for each data point three times; one for flow in each of the X, Y, and Z directions. A wireless anemometer was attached to a small tripod that was easily adjusted for height changes, as well as the capability to rotate 90 degrees for recording data in the z-direction. See Figure 6 for details.

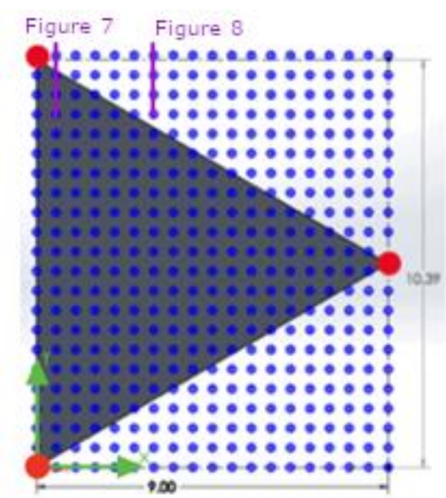

Figure 5: A digital representation of the XY grid used for data collection.

Figure 6: The anemometer reading in the X-direction.

In this experiment, we made sure that the fans were kept at the same height of 36 inches as the previous experimental setup. To ensure the correct data point was being measured, we used a makeshift plumb bob hung from the anemometer. Due to the sheer number of data points to record, we determined that three elevation planes of data would be recorded rather than the five planes used in the previous experiment. The initial plane was recorded at Z = 0, again in-line with the center of the fan blades. The other two planes were located at Z = -6 and +6 inches in our reference coordinate.

To have an idea of the flow behavior at various locations, we used MATLAB to plot the airspeed as shown in Figures 7 and 8. The results of this experiment created a wild flow pattern within the triangle, with magnitudes constantly changing. Due to this fluctuation, the data was recorded as a maximum and minimum value rather than a steady-state value. The final magnitude recorded for plotting was an average of these two values. While this will create some inaccuracies in the results, it was necessary with the limited time and inability to validate the data. The surface plots were created for the data at each X-value starting at the two fans and moving toward the third. Two examples of these plots are given in Figures 7 and 8, with their cross-sectional locations indicated in Figure 5. As expected from the turbulent data, Figure 8 shows the rapid peaks in the center of the triangle.

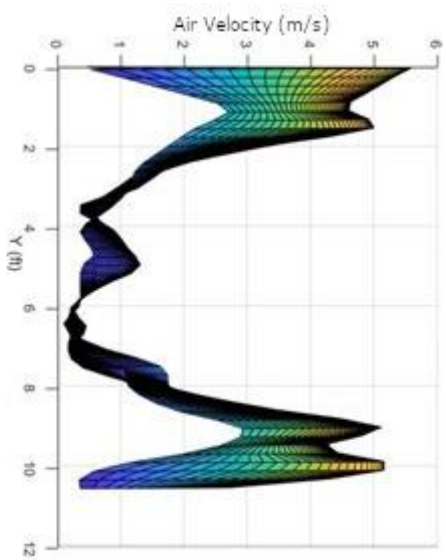

Figure 7: Magnitude of windspeed surface plot at X = 0.5 ft.

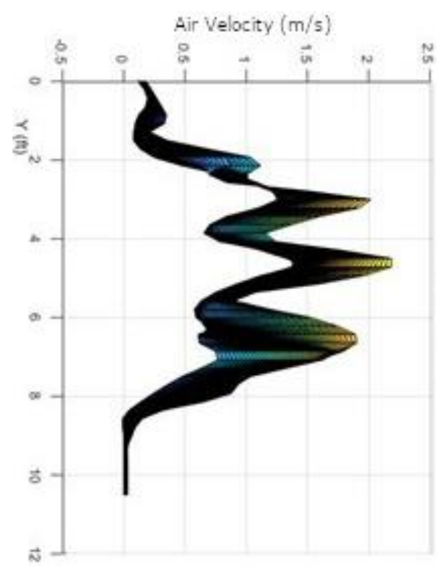

Figure 8: Magnitude of windspeed surface plot at X = 3 ft.

CASE 3: SMALL WIND TURBINE PROTOTYPE EXPERIMENT

The purpose of this experiment was to supplement the work done with the pedestal fans. However, this time a more realistic setup was conducted using a small-scale wind turbine. The experiment involved using a 20 inches wind turbine attached to a cart with a cut-off speed of 3.6 m/s. The blades were propelled by an industrial floor blower placed 16ft away from the hub of the turbine in the X direction and at the same height as the hub. Measurements were taken around the turbine using the same anemometer described earlier. The flow velocity was measured in X and Y directions, using the same 6 inches spacing grid layout that was used for the three-fans experiment. The Z direction was not recorded for this setup due to the negligible impact observed in the second experiment. All measurements were taken at the center of the turbine hub as shown in Figure 9. The turbine was placed in the center of the grid at the (X, Y) coordinate (0,5ft) relative to the same origin as the triple fans experiment. A similar plum bob approach from the previous experiment was used with the anemometer to ensure accuracy in recording the data.

At each point on the grid, for each direction, three successive measurements were taken: measuring max, min, and median values. These three measurements were necessary as values were constantly changing at each point. The collected data was then recorded in an Excel spreadsheet to be later used to create a vector field for visualization as seen in Figure 10. In this figure, the velocity vector field shows how the air is deflected in front of the wind turbine and begins to turn outward. The middle section with no velocity field vector located at X = 2ft and Y = 5ft represents the location of the wind turbine and explains why there are no measurements in that area. It can also be seen that the air sheds off the wind turbine in a triangular shape with a point of the triangle at the hub of the blades and two of the sides spreading outwards towards (10,0) and (10,8).

Figure 9: Anemometer and fan are aligned with the hub centerline.

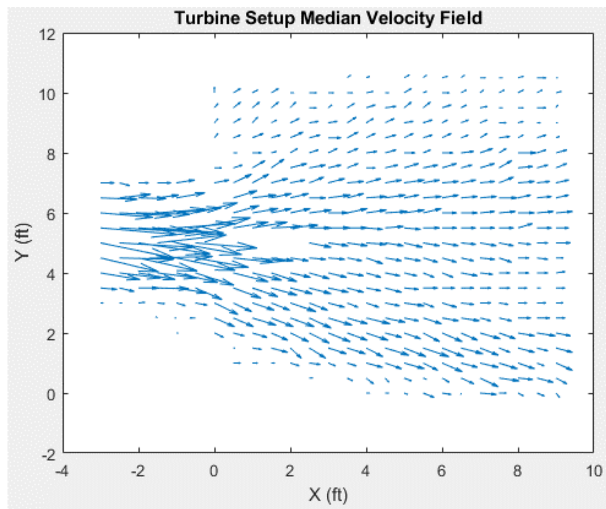

Figure 10: Velocity field showing the flow disturbance caused by the wind turbine.

CHALLENGES AND LESSONS LEARNED

The first main challenge that we encountered with the single fan experiment was identifying how to lay out the three-dimensional grid in real space. The grid could be visualized, but it was difficult to know where to place the anemometer in space. After several trials, we decided to map out an XY plane onto the floor, which was quite effective at keeping those two directions consistent. The second challenge we faced consisted of identifying how to keep the anemometer on the correct vertical plane (Z coordinate). We tried multiple methods, all of which involved taping the anemometer to a yardstick for that rigid height. We finally decided to use an overturned chair to hold the yardstick was effective, albeit a little unorthodox. The main lesson we learned from these two challenges was to fully define the constraints of the experiment before making any measurements and collecting data.

Although we gained some experience in conducting experiment one successfully, we faced some challenges with the three-fan experiment, which is time-consuming. Moreover, it was challenging for us to allocate a longer time for each experiment as most of us are full-time students and have different class schedules to preserve a common time to finish a single run at a time. This has taken a long time even though added to the urgency to complete the measurements. With all of the constraints and deadlines, we decided we expanded the data collection grid from a 3ft square to more than a 9ft square for this new setup. The new data collection took several hours, as the XY planes of data were recorded 12 times: 3 directions for each point. A total of 3,402 data values were recorded counting the individual directions. This has taken longer than we expected and made our mentors impatient as they are also constrained by the project timeline. The lesson learned from these challenges is that it is difficult to set a firm deadline especially when conducting an experimental study and making sure that the experiments are duplicated. Another challenge with this procedure was how to record the turbulent data. Within that data triangle, the airflow was constantly changing direction and magnitude. A steady state value was never reached, so we recorded the maximum and minimum values and took the average values. We found out that this approach worked to generate a rough idea of the wind velocity but left significant room for error. This exercise made us realize that discussing encountered difficulties with each other and consulting with our mentors as often as possible would make it easier for us to tackle any new challenge.

Lastly, the turbine experiment introduced a few more new challenges. Because the turbine needed to be powered by an external source, there needed to be a way of regulating the speed of the turbine to prevent it from becoming dangerous. To regulate speed, we placed a paper towel over half of the blower fan's intake to decrease the amount of air that was pushed through the turbine. This kept the turbine at a low enough speed that it remained stable and safe. Another lesson learned was during the data collection. Our team assumed that the data on one side of the turbine blade should be like the data that would be recorded on the other side. We collected a few test data points on both sides of the turbine and noticed that the data was not symmetrical enough to assume symmetric flow. After checking the experimental setup again, we realized that this could be because the experiment was conducted in a room that is not large enough, and the walls played a role in the data farther away from the turbine blade, near X = 7-9 ft.

Overall, this task of the project provided us with an opportunity to learn through hands-on applications even though we faced several challenges along the way. Even though we viewed that the data recording process of these experiments was often tedious, we believe that this practice is a valuable learning experience for all of us. We feel that we learned a great deal from this project and we encourage every undergraduate student to be involved in such an exercise as we got exposed to various learning approaches in terms of executing the project, teamwork, and managing our time between school and research requirements.

CONCLUSION

This paper illustrates our involvement as undergraduate students in a multidisciplinary team-based project. We were able to design three experiments, collected data, and analyzed the flow behavior with the aim of setting the tone for our peers and helping the other subgroups especially the drone path-planning subgroup with the information needed for the development of the “no-fly zone” for a drone. The experiments were designed to measure the airflow around fans and a small-scale wind turbine. Each experiment built upon the last one, eventually building up to the small wind turbine. We learned many lessons along the way including the challenges confronted by our team and the solutions that were attempted. Some of these challenges were more difficult than others, involving several attempts to get reliable data. We took advantage of the solutions to problems in the earlier experiments that were applied to the later ones to prevent the same issues encountered during the data collection. Overall, these experiments aided in the wind turbine research project and provided a great learning experience for all subgroups involved in this project. It is worth noting that the collected data will be used to validate the simulation results using Computational Fluid Dynamics (CFD) to mimic the experimental conditions and determine the pressure to be used in the finite element modeling (FEM) for stress analysis.

ACKNOWLEDGMENT

This work is supported by the Office of the Commissioner of Utah System of Higher Education (USHE)-Deep Technology Initiative Grant 20210016UT.

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