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A Study of the Efficiency of Toroidal Propeller Designs

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Abstract

Over the past few years, drones have become increasingly popular due to the variety of tasks that they can perform. However, one hindrance to the increase in commercial drone utilization is the noise generated by the vortices coming off the propellers. A recently proposed solution to minimize drone noise emission is the toroidal propeller, a unique design distinguished by its ring-like propeller. It is hypothesized that the closed-loop design of the toroidal propeller minimizes the tip vortices commonly generated by traditional propellers. Since tip vortices are known as the primary source of propeller noise, it is theorized that toroidal propellers reduce noise by mitigating this mechanism.

A team of engineering students studied thrust and acoustic emission of two traditional and four toroidal five-inch diameter propellers. The team of students used 3D models of the propellers in Computational Fluid Dynamics (CFD) to compare with real-world experimental laboratory data. Students have tested 3D-printed and off-the-shelf propellers to compare their performance. Students have used Ansys Fluent simulations and the Tyto Robotics Dynamometer Series 1585 Propeller Thrust Stand and RC benchmark software to compare propeller designs. The students also designed, built, and tested a safety cage that enclosed the spinning propeller, electric motor, and test stand assembly.

The purpose of this project was to develop a laboratory experimental set-up for an undergraduate aerodynamics course for the university where the engineering students are currently studying. The laboratory included 3D models of propellers for application in CFD and Stereolithography SLA printing of toroidal propeller models. The aerodynamics students will be guided through the testing and CFD simulations required to obtain values for torque, thrust, efficiency, and sound levels as a function of propeller RPM. This enables students to learn the prototyping process applicable to multiple industries, including the aerospace industry. This paper will also include a description of student outcomes, student involvement, and responses from students, as well as an assessment of student learning.

Introduction

Commercial drones have become prominent in various industries during the last decade [1]. Growing alongside this trend is the increasing concern for the noise generated by the propellers of these quadcopter drones. There has been an ongoing effort to regulate drone noise emissions in urban and residential environments [2] – [4], where drones are becoming integral to tasks ranging from videography to package delivery. The primary source of propeller noise comes from the vortex drag inherent to the traditional propeller design [5]. This technological issue provides a practical challenge that engineering students can tackle during their studies. Students are prompted to explore the mechanism of vortex formation and alternative designs that mitigate this issue. In addressing this challenge, students will not only enhance the efficiency of drone operations but also contribute to the overall environmental sustainability of drone technology in populated areas by reducing potential noise pollution.

This paper lays out a lab setup for aerodynamics students studying the aeroacoustics effects of drone propellers at varying rotational speeds. Students will be exposed to Computational Fluid Dynamics (CFD) simulations and experimental trial testing, contributing to a thorough understanding of the entire prototyping process in aerospace design. Theory will be compared to data, and student teams may hypothesize about the successes of specific propeller designs and the drawbacks of other designs. This collaborative venture, however, is about more than just mitigating drone noise. It is intended to be a catalyst for shaping the next generation of engineers. The integration of theoretical knowledge with real-world applications not only addresses an immediate technological challenge but also equips students with the multifaceted skill set needed for success in the dynamic and collaborative landscape of modern engineering.

The lab setup has been developed throughout the Fall 2023 semester and will be used in an Aerodynamics class during Spring 2024. The lab manual (Appendix A) includes step-by-step propeller testing and simulation instructions, though each team will work on a different propeller model and rotational speed. Upon conclusion of the lab, the teams are encouraged to share their data and extrapolate their data to predict how thrust, torque, efficiency, and noise change with an increase in rotational speed, addition of blades, or variation of blade geometry. The students may then be interviewed to qualitatively gauge the impact of the lab on the class's educational growth.

Theory

Traditional Propellers

Conventional propellers consist of blades with an airfoil cross-section, see Figure 1, each generating lift as the propeller rotates through the air. The blade oriented at the given angle of attack will produce a pressure differential—high pressure below the blade and lower pressure above the blade [6]. However, the high-pressure air will naturally flow to regions of lower pressure, and that can occur at the tip of these blades. These swirling air masses at the blade tips are named "tip vortices", see Figure 2. The vortices are a primary source of noise and energy loss in traditional propellers [7], [8], and several innovative designs have attempted to minimize tip vortices by modifying the geometry of the propeller tip.

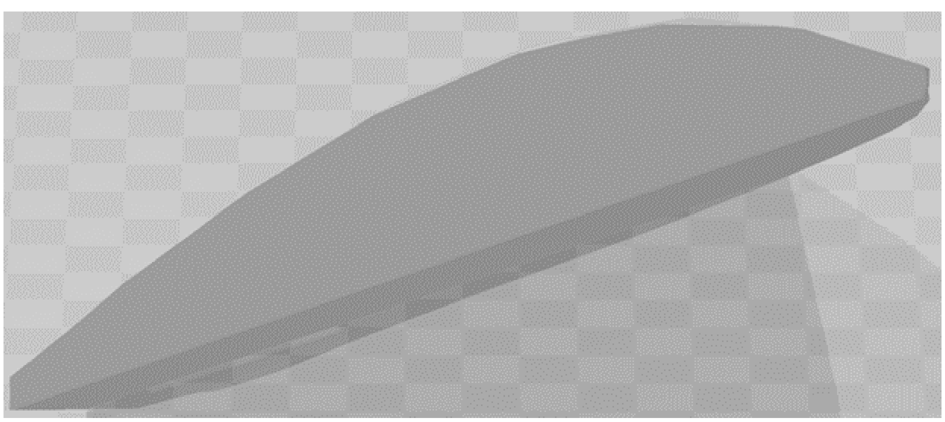

Figure 1. GemFan 5040 blade cross-section.

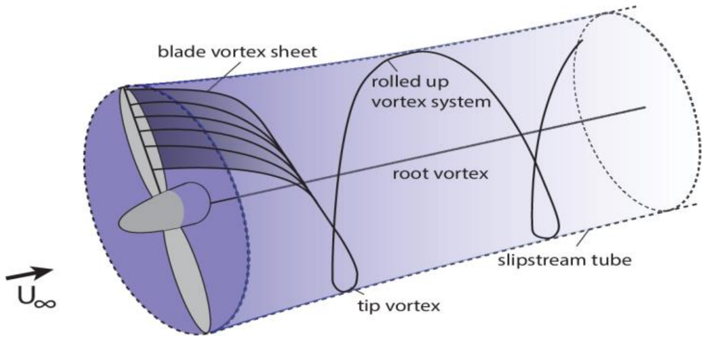

Figure 2. Diagram of a propeller tip vortex [9].

Toroidal Propellers

Toroidal propellers, a relatively new type of propeller, see Figures 3 - 4, offer a promising solution to the challenges posed by traditional propellers. Unlike traditional propellers, toroidal propellers have ring-like blades with one tip connecting to another. This unique design spreads the location of vortex formation to a larger area, thus decreasing the magnitude of the vorticity and, potentially, reducing noise and increasing efficiency [7], [8]. This distinct feature makes toroidal propellers an intriguing alternative for applications where noise reduction is paramount.

Figure 3. Injection molded 2-bladed toroidal propeller.

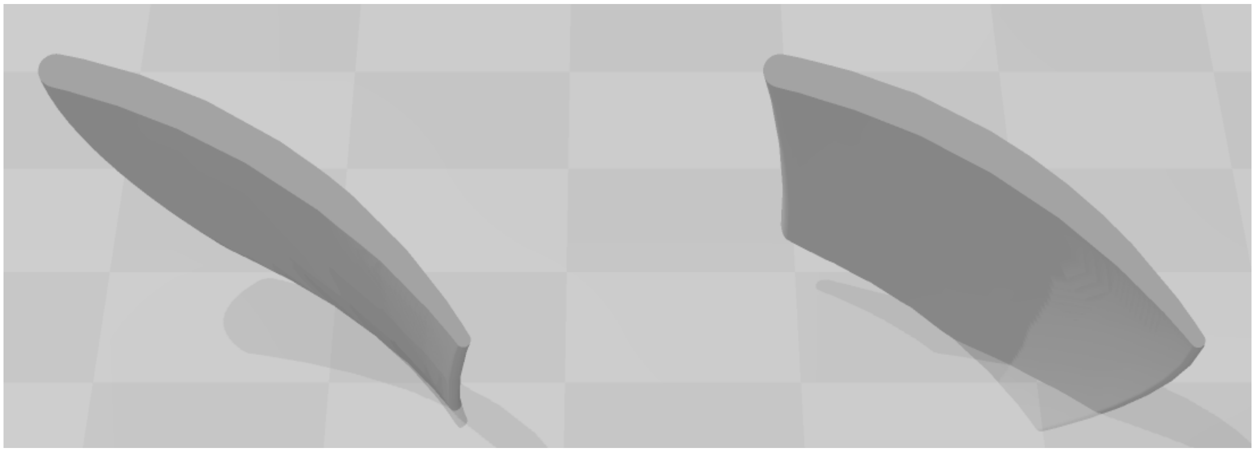

Figure 4. Toroidal propeller cross-section.

Theory

The following theory serve as fundamental tools for evaluating propeller performance, allowing for a quantitative comparison between traditional and toroidal designs. The coefficients facilitate the translation of theoretical principles into measurable parameters, which are used to improve propeller design. The thrust coefficient [10] is defined as

$$C_T = \frac{T}{\rho n^2 d^4}, \quad (1)$$

where T (N) is propeller thrust, ρ (kg/m^3) is air density, n (rev/s) is rotational speed of the propeller, and d (m) is propeller diameter.

Similarly, the torque coefficient [10] can be defined as

$$C_\tau = \frac{\tau}{\rho n^2 d^5}, \quad (2)$$

where τ (Nm) is propeller torque. The advance ratio [10] is defined as

$$J = \frac{V}{nd}, \quad (3)$$

where V is the axial flow velocity. The propeller mechanical efficiency [11] is defined as

$$\eta = \frac{V}{2\pi n}\frac{\mathrm{T}}{\tau} = \frac{J}{2\pi}\frac{C_T}{C_\tau}, \quad (4)$$

Surface roughness and turbulent flow result in noise generation. As a propeller spins faster, the air near the blade tips experiences higher velocity differences and pressure gradients, leading to increased turbulence. Any imperfections or roughness on the propeller blades can disrupt the smooth flow of air and contribute to the formation of turbulent eddies. The air flowing over the propeller blades creates a thin layer of turbulent flow along their surfaces. This boundary layer becomes increasingly turbulent at higher speeds and near the blade tips. The Sound Pressure Level *SPL* and Sound Power Level *SWL* and related equations are useful in determining aeroacoustics.

$$SPL = 20\, log_{10}\left(\frac{p}{p_{ref}}\right), \quad (5)$$

where p is the root mean square sound pressure of the sound wave and p_{ref} is the reference sound pressure (20 micro pascals).

$$SWL = 10\, log_{10}(W/W_{ref}), \quad (6)$$

where W is the acoustic power radiated by the sound source and W_{ref} is the reference acoustic power (1 picowatt). In the pursuit of accuracy and reliability, the given equations offer a rigorous framework for propeller analysis, enabling students to have a deeper understanding of the complex interplay between design parameters and performance outcomes.

Implementation

Apparatus

The experimentation will take place in a safety cage with each side being 41 inches long. The cage's frame consists of aluminum beams with a track on all sides with ¼" stainless steel wire mesh, see Figure 5. One of the sides of the cage also functions as a door, with the knob being able to screw into the frame, securing the content inside of the cage.


Figure 5. Student designed safety cage

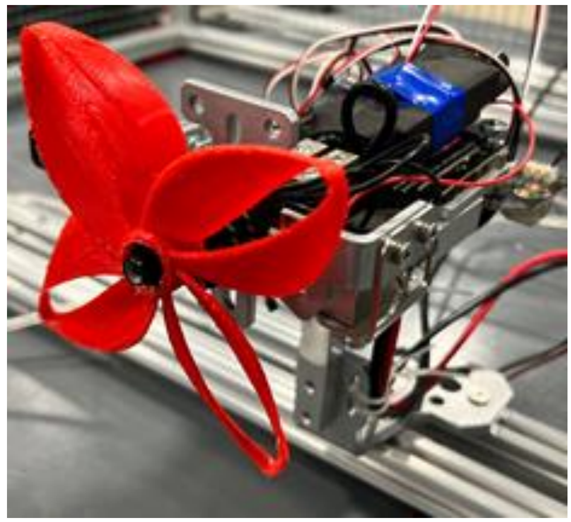
Figure 6. Tyto Robotics 1585 Thrust Stand

The dynamometer and pitot tube setup consist of the Tyto Robotics Series 1585 Thrust Stand Dynamometer. The dynamometer is secured to an aluminum beam running across the bottom of the cage, see Figure 6. Its purpose is to measure the thrust produced by the propeller, efficiency, rpm, torque, and power. In front of the dynamometer is the pitot tube, situated to measure the wind velocity from the propeller. The dynamometer is powered by a battery and exports data to the computer handling the recording software. A switch system was also created to turn on and off the dynamometer and change the rotational direction of the propeller, see Figure 7.

Figure 7. Switchbox to control power and rotational direction of propeller.

RCBenchmark is the software used to record the propellers' metrics, see Figures 8 – 9. The dynamometer feeds the recordings to the application through a wired connection. The software has many capabilities, including automatically and manually controlling the power input of the dynamometer and reading a multitude of quantities from the dynamometer. As output, the software is also capable of creating *.csv* files, which can be analyzed by the student using Excel.

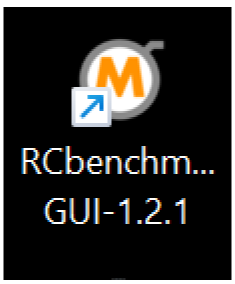

Figure 8. Desktop icon, RCBenchmark

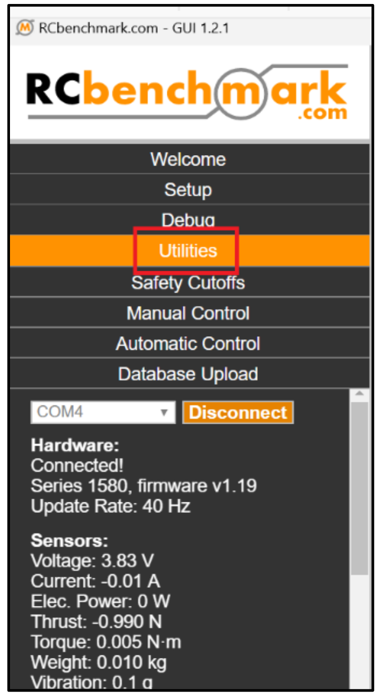

Figure 9. Screenshot of RCBenchmark dashboard.

The BAFX3608 Digital Sound Level Meter is also used during experimentation to monitor the sound levels produced by propellers, see Figure 10. This meter is equipped to record the highest decibel level during a given span of time until reset. For the laboratory, this is convenient as the students will only need to record the highest level of decibels for each trial. The sound level meter sits next to the safety cage, see Figure 11, meaning it can also pick up noise from the surrounding. Therefore, it is imperative that students make no noise as the propeller is tested.

Figure 10. Digital Sound Level Meter.

Figure 11 Sound level meter next to safety cage.

CFD simulations of various propeller types were conducted using Ansys Fluent as the primary software. 3D propeller models were used and STL and STP files were generated using SOLIDWORKS. The STP files were subsequently employed in Ansys Fluent to conduct simulations, focusing on assessing thrust forces and acoustic characteristics at 10,000 propeller revolutions per minute.

Starting in Ansys DesignModeler, cylindrical enclosures had to be made with a rotating domain around the propeller and a non-rotating domain for the far-field. The mesh sizing was set to 2 inches for the outer enclosure mesh and 1 inch for the rotating propeller mesh. In Fluent, the k-epsilon turbulence model was used for the calculations. For the acoustic data, the Ffowcs Williams & Hawkings equation was selected. This gives both a dB calculation as well as a sample sound from the propeller. To get data for thrust force, it must be selected in the Report Definition section. The time step size was set to 0.00015 seconds and the number of time steps was set to 10 with maximum iterations per timestep set to 15. Running these simulations with these settings, details of thrust force and acoustic properties can be obtained and compared to actual values obtained from experimental testing.

Results

The results from the experimental tests are outlined in Table 1 and propellers used in the experiments are shown in Figure 12. The injection molded propellers have a higher thrust than their 3D resin printed counterpart. The 3 and 4-blade 3D resin printed toroidal propellers have lower thrust and higher sound level than the 2-blade printed toroidal propellers.

Table 1. Summary of experimental data for propellers A – F.

Propeller	**Manufacturing Process**	**Thrust *T* (N)**	**Peak dB**	**RPM**
2-blade traditional (A)	Injection Mold	2.4	70	10529
2-blade traditional (B)	3D Resin Printer	0.339	66	10028
2-blade toroidal (C)	Injection Mold	1.79	63	10236
2-blade toroidal (D)	3D Resin Printer	1.67	80	9750
3-blade toroidal (E)	3D Resin Printer	1.39	83	10137
4-blade toroidal (F)	3D Resin Printer	1.39	84.5	10104

A B C D E F

Figure 12. Different propellers A – F used in experimental testing.

The CFD simulation results are shown in Figures 13 – 16. Initial simulation show the same trend as in experiments of decreasing thrust with increasing number of toroidal blades while the trend for sound levels goes in the opposite direction and contradicts the experiments. Further detailed simulations including mesh studies will be needed to reach further results from simulations that are in line with experiments.

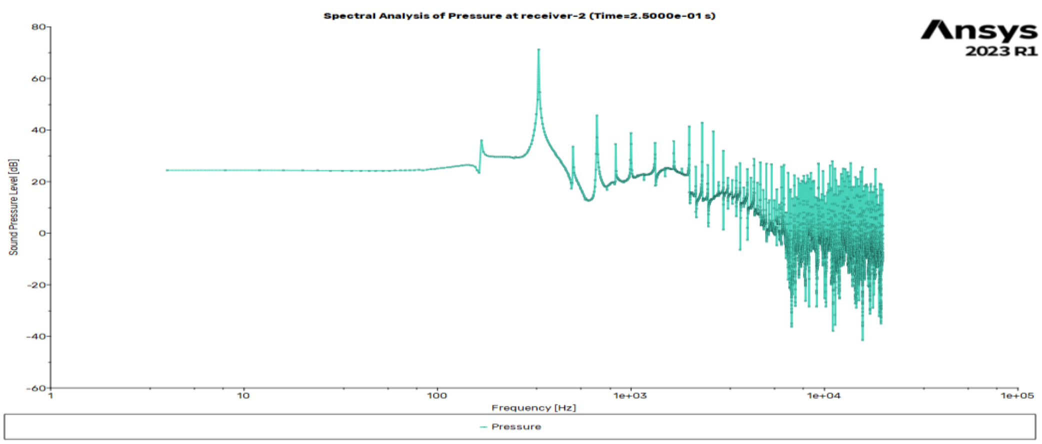

Figure 13. 2-blade toroidal propeller FFT plot, SPL = 71.5 dB

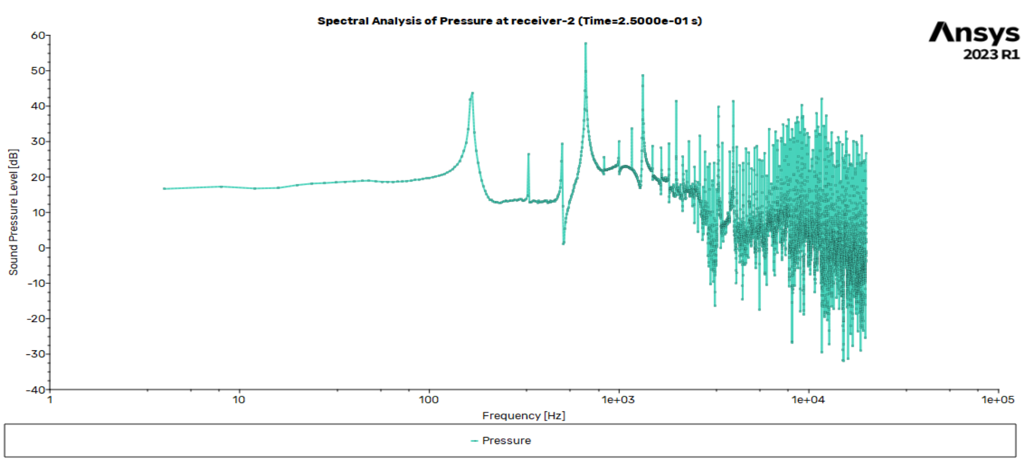

Figure 14. 4-blade toroidal propeller FFT plot, SPL = 65.5 dB

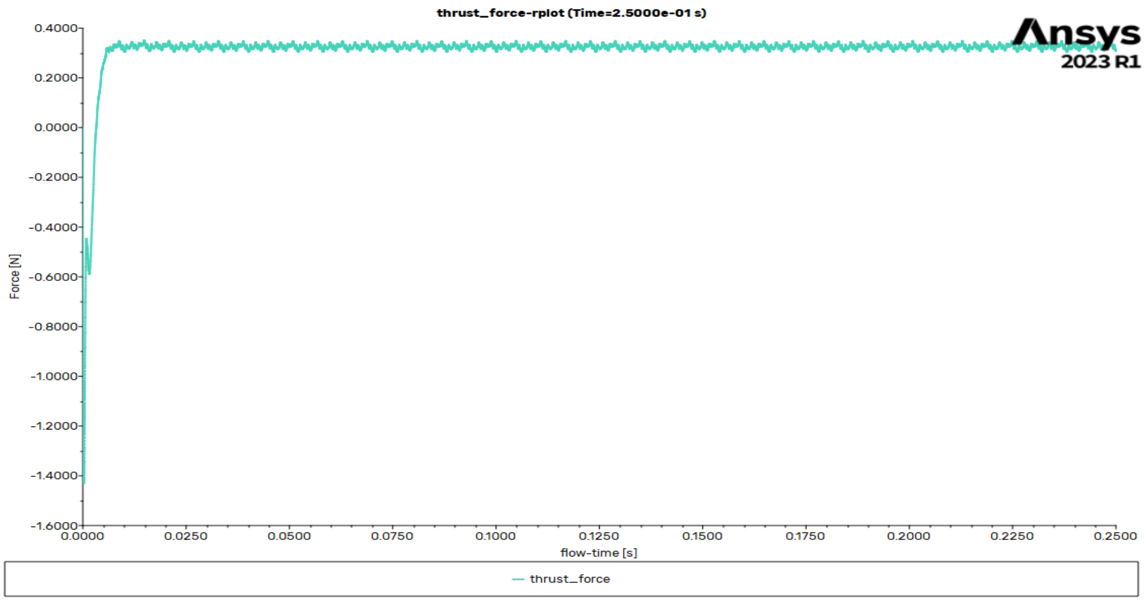

Figure 15. 2-blade toroidal propeller thrust plot.

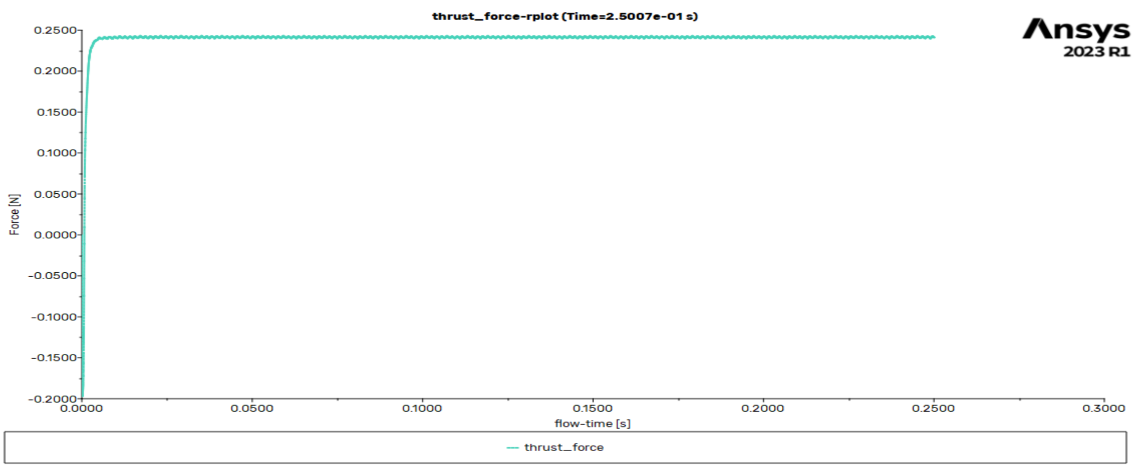

Figure 16. 4-blade toroidal propeller thrust plot.

Discussion

In aerospace engineering, the analysis of various propeller types, encompassing both standard and toroidal designs, provides valuable insights into their performance characteristics. It was determined that the primary focus on thrust and noise level is crucial for the laboratory experiment, as these parameters are pivotal in determining the overall effectiveness of propellers in practical applications.

Six types of propellers were tested and analyzed including 2 -blade standard propellers and 2, 3 and 4-blade toroidal propellers. Upon analyzing the data depicted in the results section, it was evident that the 2-blade traditional propeller stood out first since it had the highest thrust out of those tested. From a performance standpoint, the standard 2-blade propeller stood out among the best, but another outstanding propeller type was the 2-blade injection molded toroidal propeller.

It was quieter than other propellers and this is reinforcing the notion that one of the benefits of the toroidal propeller is its relative lower sound level. An important advancement in drone technology has been to decrease the noise emitted by drones, so finding a more quiet propeller design is an important step toward this goal.

The university plans on continuing this experiment as part of an aerodynamics lab. There are a couple of ideas to expand on the tests, with the first being to experiment with different propeller designs. Students can test only a limited number of propeller types in the time that they are given, but they would like to test more designs to continue searching for the most optimized propeller. The students would also like to test the same designs but made with different materials to determine the effects of the material on performance. A majority of the propellers for this test were made using UV-sensitive resin, so it would be interesting to see how different materials will affect the overall performance of the propeller.

Student Assessment

The overall objective was to engage students in a manufacturing processes and aerodynamics related project through design, fabrication and assembly of a test stand and safety cage for propellers. This project was included in the manufacturing processes course during the Fall 2023 semester for implementation as a laboratory in the aerodynamics course during the Spring 2024 semester. For the manufacturing processes course, the students submitted project progress reports and wrote a final project report. The course project contributed to 10% of the final grade.

The student performance was assessed based on written final report but also on the monthly progress reports and achievements in relation to the definition of completeness for the project. In the monthly progress reports, students provided evidence of work completed during the past month and included an updated time line for the project. The project final report generally included an abstract followed by an introduction to the topic, a theory section, a results section, a section with conclusions, recommendations for the project, and references.

The project described in this paper contributed to certain university course outcomes such as personal resilience, intellectual pursuit, global engagement and bold vision as shown in Table 2. The project was not the only component that contributed to Table 1 for this course. Other evaluation procedures such as quizzes, homework problems, labs, exams, and final exam determined the final level of contribution.

Table 2: Manufacturing processes course inventory for university student learning outcomes

This course contributes to the University and program outcomes as indicated below:
Significant Contribution – Addresses the outcome directly and includes targeted assessment.
Moderate Contribution – Addresses the outcome directly or indirectly and includes some assessment.
Minimal Contribution – Addresses the outcome indirectly and includes little or no assessment.

OUTCOMES	Significant	Moderate	Minimal
Intellectual Pursuit			
ABET: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.		X	
ME 461: Discuss and explain casting processes.	X		
ME 461: Discuss and explain hot and cold working of metals.		X	
ME 461: Discuss and explain joining: soldering, brazing and welding bonding.	X		
ME 461: Discuss and explain machining.	X		
ME 461: Discuss and explain plastic processing: molding and extruding.	X		

The student learning outcomes specific for the manufacturing processes course were to discuss and explain the following:

A. Discuss and explain casting processes.
B. Discuss and explain hot and cold working of metals.
C. Discuss and explain joining: soldering, brazing and welding bonding.
D. Discuss and explain machining.
E. Discuss and explain plastic processing: molding and extruding.

The project included components related to outcomes C and D.

Overall, this project brought important insight for the students involved. The students learned to use Ansys Fluent, a software that they can greatly benefit from during their professional career. This project gave the students real-world experience with 3D printing and experimental measurements. The students were also able to examine a new type of propeller design in the form of a toroidal propeller and test this new, potentially pioneering design.

Reproducing this project and associated lab in a classroom setting can benefit engineering students. Firstly, utilizing Ansys Fluent software to replicate this project has the potential to generate new, innovative and optimized propeller designs. This project is an excellent introduction for students to an engineering problem where there is a lot of potential for improved efficiency from an optimized design. It allows students to engage in the engineering research, design, and development phases. Moreover, students who aspire to pursue graduate-level education may find this project intriguing as it can help familiarize them with the research environment.

Conclusion

By continuing research on propellers, the university can contribute to developing quieter and more efficient drones while fostering the next generation of aerospace engineers through hands-on learning experiences. This will lead to advancements in propeller design and aerospace education, paving the way for a future where drones and other propeller-driven machines operate with minimal noise pollution. The lab to be produced promises the following educational and technological impact:

1. Propeller design: The study identifies promising design features for future low-noise propellers for drones.
    - Expanding the testing range to encompass a wider variety of propeller designs and materials.
    - Investigating the impact of propeller size and blade geometry on performance.
2. Experimental learning: The developed laboratory setup provides a valuable tool for undergraduate aerodynamics students to learn experimental procedures and data analysis techniques.
3. Computational modeling: The study demonstrates the use of CFD simulations for predicting propeller thrust and sound levels, promoting the use of computational tools in aerospace education.

4. Expands the frontier: This research fills a critical gap in the existing literature by comprehensively comparing traditional and toroidal propellers, alongside its educational impact.

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Appendix: Propeller Testing Lab Manual

Abstract

In this laboratory experiment, the aim is to investigate the performance of propellers using a Tyto Robotics dynamometer. The primary objective is to measure and evaluate various parameters, including thrust and sound levels to gain insights into the behavior of propellers. To achieve accurate and meaningful results, the equipment is to be properly calibrated, ensuring the reliability of the collected data. This laboratory handout outlines the materials and equipment used in the laboratory experiment and the calibration process, setting the stage for a comprehensive analysis of experimental propeller performance.

Objective

In this lab, the goal is to test and analyze the performance of propellers. Students will learn how to measure and evaluate parameters such as thrust and sound levels to understand the behavior of propellers.

Introduction

In the realm of aerospace engineering and propulsion systems, understanding the intricate dynamics of propellers is of paramount importance. Propellers serve as essential components in aircraft and marine vehicles, dictating their performance and efficiency. To delve into propeller behavior, this laboratory experiment employs a precision instrument known as a dynamometer. Through this experiment, the aim is to measure and evaluate key parameters including thrust and sound levels, shedding light on the performance characteristics of various propeller designs.

To grasp the fundamental principles governing propeller performance, several equations come into play. The thrust coefficient is defined as

$$C_T = \frac{T}{\rho n^2 d^4},$$

where T (N) is propeller thrust, ρ (kg/m³) is air density, n (rev/s) is rotational speed of the propeller, and d (m) is propeller diameter. The torque coefficient is defined as

$$C_\tau = \frac{\tau}{\rho n^2 d^5},$$

where τ (Nm) is propeller torque. The advance coefficient or advance ratio is defined as

$$J = \frac{V}{nd},$$

where V is the axial flow velocity. The propeller mechanical efficiency is defined as

$$\eta = \frac{V}{2\pi n}\frac{T}{\tau} = \frac{J}{2\pi}\frac{C_T}{C_\tau},$$

Materials and Equipment

Measurement instruments (e.g. anemometer, pressure sensor, sound meter).
Propellers of various types
RC Benchmark Data acquisition software
Safety cage
Safety equipment (goggles, gloves etc.).
Tyto Robotics Series 1585 Thrust Stand Dynamometer

Safety Note

Before commencing the experiment, it is crucial to ensure that no loose objects are present near the safety cage intake. Loose items could be blown away from the chamber, potentially causing damage to the equipment and may injure individuals in the vicinity. Additionally, anyone working near the safety cage door should exercise caution and wear appropriate personal protective equipment (PPE) to prevent injuries caused by debris that might be unintentionally blown away from the testing chamber. **Safety glasses are required for this lab.**

Preparation of Materials

1. Choose four of the ten available propeller types to test, see Figure 1. To eliminate extra work, it is recommended that you choose four propellers that will produce thrust when rotated in the same direction. These propellers are designed for drones, so while some may rotate clockwise to produce thrust, others may be spun counterclockwise.

Figure 1. Top row (left to right): Dalprop Donut injection molded toroidal propeller, 2-blade “sharp” printed toroidal propeller, 3-blade “sharp” printed toroidal propeller, 4-blade “sharp” printed toroidal propeller. Middle row (left to right): 3-blade “rounded” printed toroidal propeller, 4-blade “rounded” printed toroidal propeller, 5-blade “rounded” printed toroidal propeller. Bottom row (left to right): 2-blade injection molded standard propeller, 2-blade printed standard propeller, 3-blade printed standard propeller.

2. Open the RC Benchmark app and click the Utilities tab, see Figures 2 - 3. From here, check to see that the torque, thrust, and weight have all been calibrated. If they have not been previously calibrated, let the instructor know and follow steps 2 through 7 to calibrate the dynamometer. If the dynamometer is already calibrated, move on to step 8.

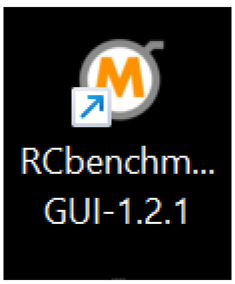

Figure 2. Desktop icon for RC Benchmark app.

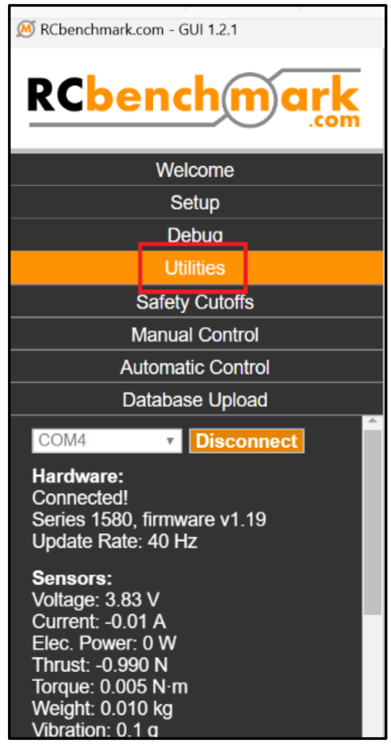

Figure 3: Select "Utilities" tab.

3. Before calibrating, make sure the battery for the dynamometer is turned off (Left switch is in OFF position). The first calibration that should be made is for the torque. To start, slightly loosen the fasteners on the no-solder board and slide the board back as far as you can. Take a 5/64" Allen wrench and unscrew the motor from the front of the thrust stand and place the motor screws in a safe, confined space. Leave all wiring as it is.

4. To properly calibrate the thrust, the safety cage must be flipped on its back, see Figure 4. After clearing an empty space, begin slowly tilting the cage back 45 degrees. Once there, move any cluttering wires to the underside of the cage. Continue tilting the chamber until it is laying on its back.

Figure 4. Safety cage on its back

5. Take the 200g weight as shown in Figures 5 - 6 and follow the thrust calibration instructions as shown on the RC Benchmark app. The software will run the calibration for you.

Figure 5. 200g weight for calibration

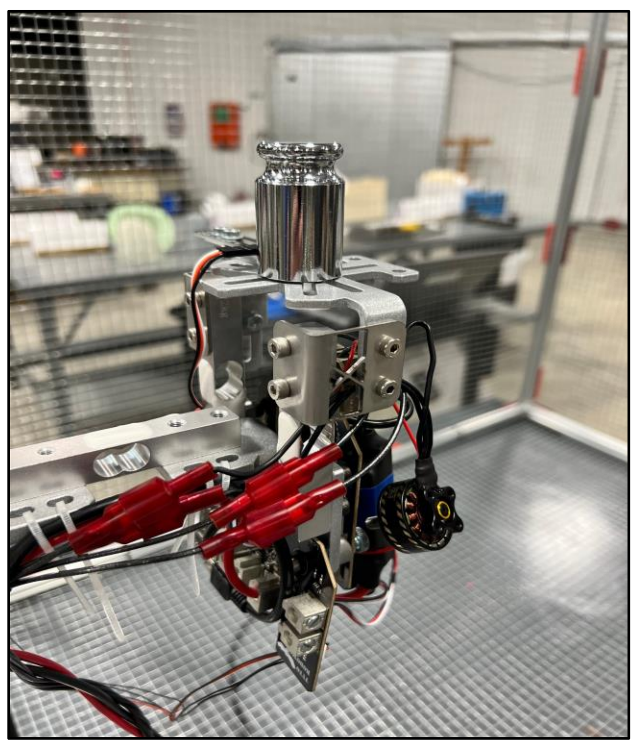

Figure 6. Weight resting on motor for calibration

6. Once the calibration is complete, remove the 200g weight and begin tilting the chamber back to being right side up. Remember to move all wiring back to behind the chamber. Once upright, screw the motor back into place and slide the no-solder board up. Don't forget to tighten the fasteners.

7. The weight and torque calibrations are done by the software. Take the measuring board and attach it to the dynamometer as shown in Figure 7 below. Once attached, follow the instructions for the weight and torque calibrations as presented on the RC Benchmark software. Remove the measuring board once the calibrations are complete.

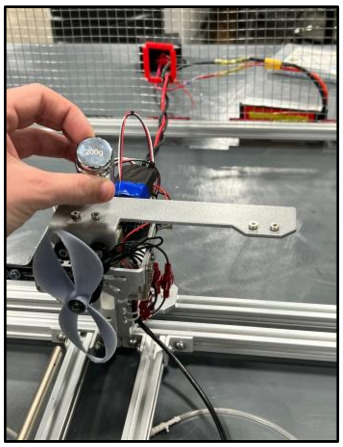

Figure 7. Weight and attached measuring board for weight and torque calibrations.

8. Place the microphone in a secure place next to the testing chamber, see Figure 8. Make sure one team member is monitoring it at all times during the experiment to prevent it from being blown off during the experiment.

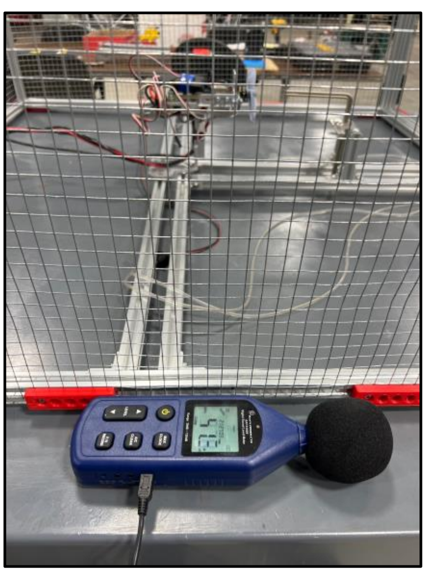

Figure 8. Microphone secured next to cage.

9. On the measuring screen, check to see that information for the thrust, torque, power, airspeed, and efficiency is being graphed. Press "Tare Load Cells" on the bottom left-hand corner of the screen as shown in Figure 9. If all the information is being presented, you can move on to the procedure. If you are receiving any irrational data, talk to your instructor before moving on.

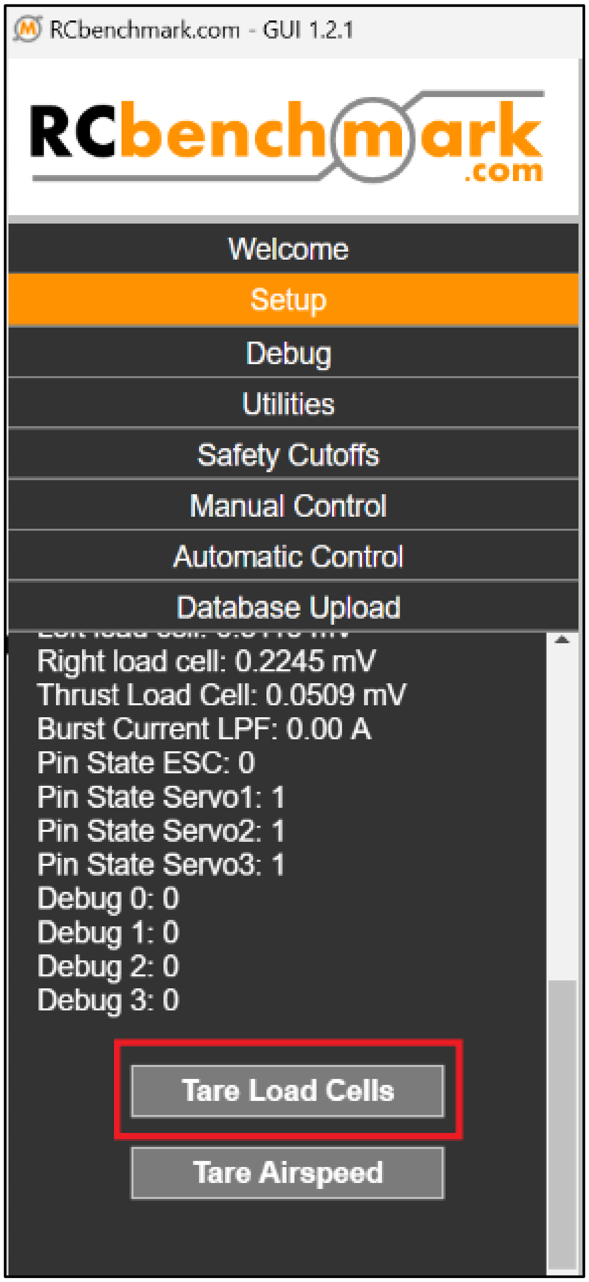

Figure 9. Select the "Tare Load Cells" button.

Procedure

10. Open the cage door and install the first propeller. Use the 8mm (¼" Drive) socket wrench to tightly fasten the cap on the drive shaft, see Figure 10. Check to see that the propeller is firmly held in place.

Figure 10. Socket wrench fastening the cap on the drive shaft.

11. Close and lock the door to the testing chamber. Open the Safety Cutoffs tab, see Figure 11a) and check the power, thrust, and torque cutoffs. If these cutoffs seem too low, raise them near to the maximum allowable cutoffs as indicated by the software, Figure 11b). If the cutoffs are too low, the dynamometer will be shut down when they are exceeded.

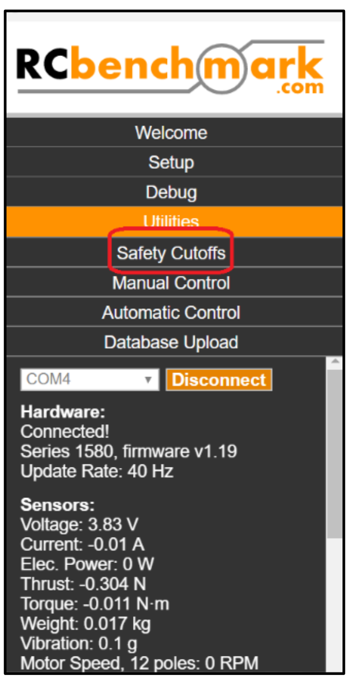

Figure 11a) Select the "Safety Controls" tab.

	Min	Max	System
Voltage (V)	0	15	0 / 50
Continuous Current (A)	-55	55	-55 / 55
Burst Current (A)	-60	60	-60 / 60
Power (W)	0	2000	0 / 2750
Thrust (N)	-49.0	49.0	-49 / 49
Torque(N·m)	-0.5	0.5	-2.0 / 2.0
Motor Rotation Speed(RPM)	0	80000	0 / 83000
Vibration (g)	0	4	0 / 8
Temperature 74SQ (ºC)	10	60	-10 / 120
Temperature 686C (ºC)	10	60	-10 / 120

Figure 11b). Adjust minimums of power, thrust, and torque.

12. Turn on the battery for the dynamometer, see Figure 12. The motor should begin ticking when this happens. If it does not, notify your instructor and check for any loose or disconnected wires.

Figure 12. Battery power switch (left) and blade rotation switch (right).

13. Open the Manual Control Tab and checkmark the ESC slider as shown in Figure 13. Test to see if the motor is rotating in the right direction by slowly raising the ESC power level. Once the propeller begins spinning, bring the ESC power back down fully. If the motor is not spinning in the right direction, flip the control switch next to the battery and repeat this test. Once the motor is rotating in the proper direction, move on to the next step.

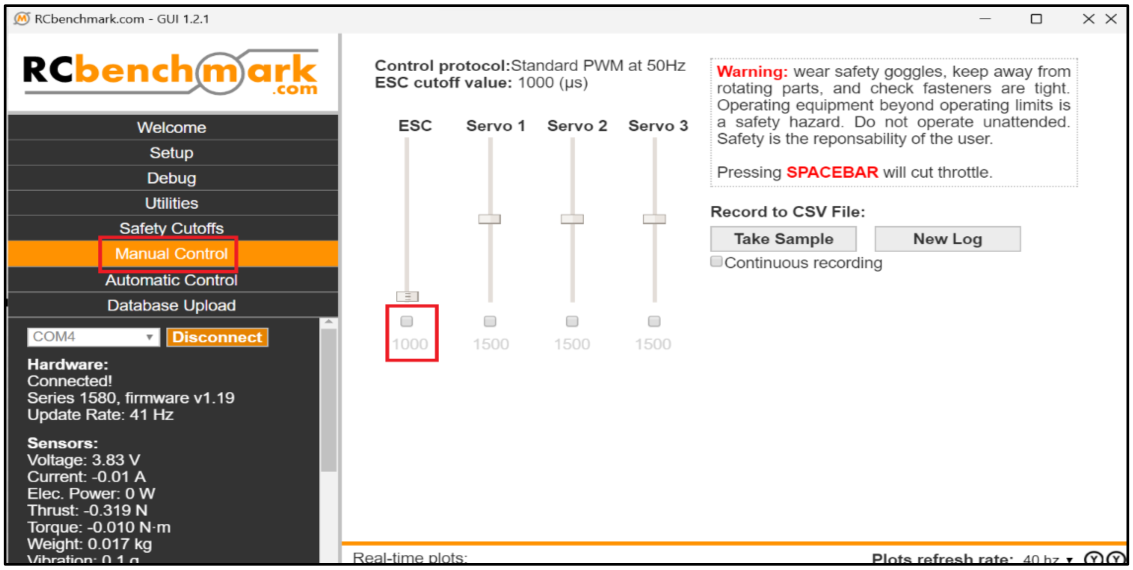

Figure 13. Select the "Manual Control" tab and check the ESC box.

14. Activate the microphone if it is not already on. Slowly turn the ESC power up until it is near a power level of 1500. Keep the power level here and press the "Take Sample" button to record the data on a csv file, see Figure 14. Bring back down the ESC power level. Record the decibel level in the tables below. Open the *csv* file and record the data from it as well.

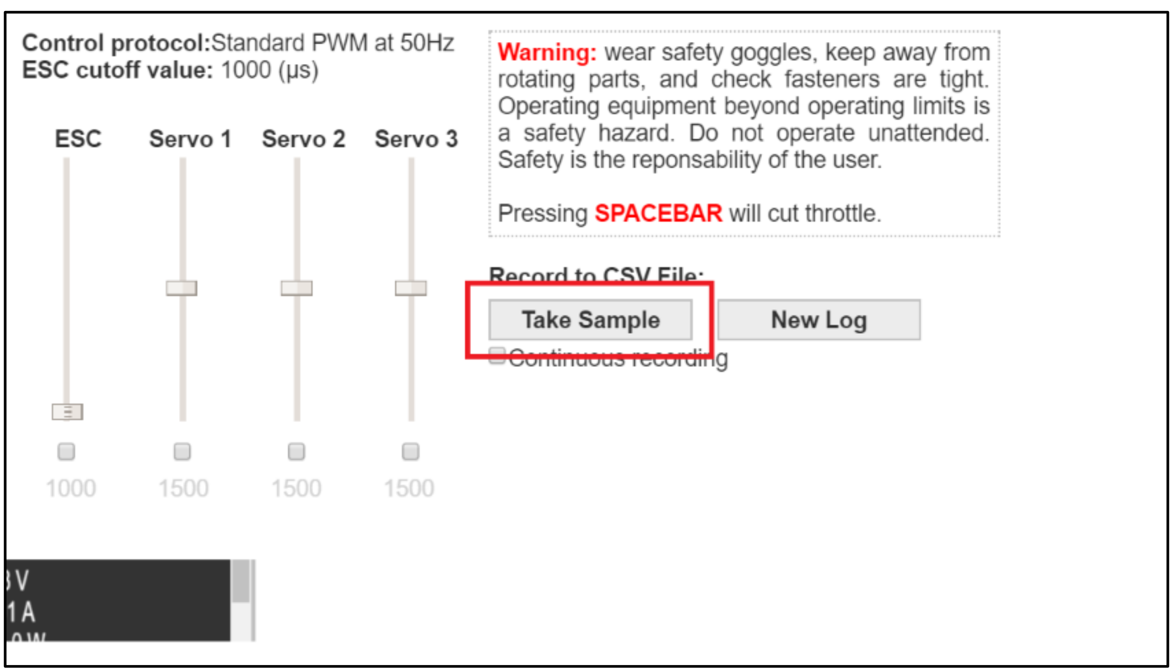

Figure 14. Select the "Take Sample" button.

15. To measure the decibel level of each trial, press the “Max Clock” button on the microphone to record the maximum decibel level of the trial, see Figure 15a). **It is essential that all members are quiet to obtain accurate measurement.**

Figure 15. Press the “Max Clock” button to record maximum decibel level.

16. Repeat the previous step five times, then carefully remove the propeller from the dynamometer. **Do not open the cage until the dynamometer comes to a stop and the battery is turned off.**

17. Repeat these steps for the other three propellers.

<u>Data</u>

1. Propeller #1: Propeller Type: ___________________

#	RPM	Sound level (dB)	Thrust (N)	Torque (N·m)	Efficiency (%)
1					
2					
3					
4					
5					
6					

2. Propeller #2; Propeller Type: ___________________

#	RPM	Sound level (dB)	Thrust (N)	Torque (N·m)	Efficiency (%)
1					
2					
3					
4					
5					
6					

3. Propeller #3: Propeller Type: ___________________

#	RPM	Sound level (dB)	Thrust (N)	Torque (N·m)	Efficiency (%)
1					
2					
3					
4					
5					
6					

4. Propeller #4: Propeller Type: ___________________

#	RPM	Sound level (dB)	Thrust (N)	Torque (N·m)	Efficiency (%)
1					
2					
3					
4					
5					
6					

Analysis

Based on your test results, which propeller type had the greatest overall efficiency?

____

Which propeller type had the highest thrust?

____

Which propeller type was the quietest?

____

Taking your previous answers into consideration, along with any other data you received, which propeller design is the most optimal in your opinion? Please explain your choice.

____

____

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