Utilizing Biological Airfoils to Reduce the Acoustic Noise Produced by Wind Turbine Blades

Grant Proposal

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Executive Summary (Eng)

Wind turbines are a beneficial source of renewable energy to aid in the shift from fossil fuels. The burning of fossil fuels drives climate change and global warming, as well as induces medical complications. However, wind turbines generate noise, resulting in sound regulations that limit energy production, therefore making it more expensive to produce the same amount of energy. To maximize the total amount of power available through wind turbines, they must have their acoustics reduced, because of regulations placed on them limiting the potential of wind energy. The main source of noise originates in air turbulence from the blades moving through the air. Therefore, there is a need to reduce the aerodynamic noise from the wind turbine blades. This study investigates different biological airfoils as inspiration for noise reduction. Research has already been conducted on owls to attempt to utilize certain wing characteristics to decrease the acoustics of airfoils. This experiment will use bat wings due to their silence, penguin wings due to their performance in water, and pterodactyl wings to lower the overall sound pressure levels (SPL) produced by wind turbines while maintaining efficiency.

Keywords: clean energy, wind turbines, airfoils, acoustics, sound pressure levels, biological airfoils,

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Wind turbines generate sound as a byproduct of their operation. While some sound is produced, it can still be enough to disrupt local residencies as well as local ecosystems. As a result, regulations and restrictions are placed on wind turbines, limiting the total amount of power they generate from their potential. The goal of this project is to test naturally occurring airfoils, to determine whether new wind turbine blades can model specific characteristics to reduce the acoustics that are produced. An airfoil is an object that creates a combination of drag and lift when it moves through a fluid (Britannica, 2023).

Climate Change and Pollution

Pollution and climate change are two continuously growing problems. The large-scale emission of fossil fuels as a source of energy contributes to various health-related issues, especially in children. Some of these issues include delays in behavior and cognitive ability, respiratory-related sickness, as well as other chronic illnesses (Perera, 2017).

According to the Intergovernmental Panel on Climate Change, the Working Group I's Sixth Assessment Report stated that the average temperature of Earth's atmosphere could increase by up to 1.5 °C by 2040 (Masson-Delmotte et al., 2021). This increase in global temperature will contribute to many global problems, meaning that the longer it remains unaddressed, the harder it becomes to solve. Wind turbines are a rising source of renewable energy to aid in combating climate change and global warming. Wind turbines are growing in popularity and can generate more and more energy (Friedlander, 2021).

Wind Turbine Sound

Although environmentally friendly, wind turbines generate noise that can harm nearby residents and local ecosystems. Especially as wind turbines continue to become larger, they cause an increase in tip speed, resulting in greater sound power levels. Noise produced by wind turbines originates from two main sources, the blades moving through the air and the mechanical components. The larger contributor to the overall noise produced by wind turbines is the blades themselves moving through the air (Wind Turbine, n.d.). This type of noise is broadband noise, which occurs when multiple frequencies are joined together. Wind turbines generate broadband noise that sounds like a whooshing noise white-noise (U.S. Department of Energy, n.d.). As a result of the noise created by wind turbines, they have regulations based on sound pressure levels at nearby residencies, limiting both where they can be placed and how many can be installed (Hoen et al., 2023). These regulations have led to different approaches to reducing wind turbine noise, including the study of different naturally occurring airfoils.

Biomimicry

Biological structures (like wings) have inspired the designs behind countless numbers of airfoils. An example of animal wings being used to improve the efficiency of airfoils would be seagull wings. Seagull wing structure has been used due to its optimal aerodynamic performance, entailing a high lift-to-drag ratio, indicating the high efficiency of the airfoil. As a result, seagulls can generate lots of power aiding them in a variety of wing conditions, especially living by the coast (Hua et al., 2019). However, when it comes to noise emissions, seagulls are intentionally loud, and they are especially loud when compared to owls (Barry, 2021). Owls have evolved to fly silently to enable them to approach their prey without being detected. There are a few key feather adaptations that enable owls to fly near silently. The prominent features are trailing-edge fringes, leading-edge serrations, and smooth velvety feathers (see Figure 1).

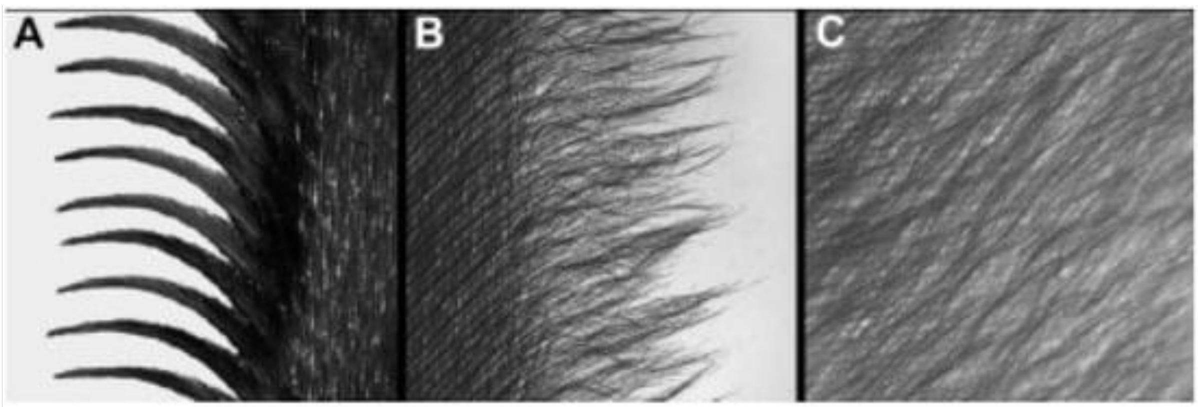

Figure 1. Figure one shows the adaptations of a barn owl, including leading-edge serrations, trailing-edge fringes, and its soft coat (Wang et al., 2019).

The trailing edge fringes force the airstream above and below the wing to converge, resulting in the absence of noise-producing vortices. The velvety feathers aid in reducing trailing edge sound by lowering the streamline speed along the trailing edge. Leading edge serrations are the most prominent element that contributes to silent flight by helping to eliminate turbulent boundary layer noise by causing the streamline to stay steady along the wing. An owl's typical leading-edge serrations consist of sinusoidal serrations and sawtooth serrations. These four qualities possessed by owls have been integrated into different types of airfoils as methods of noise reduction (Wang et al., 2019). However, there is already extensive research that has been conducted on owl wings, therefore this study will examine different biological airfoils.

Section II: Specific Aims

Objective

This proposal aims to explain background information regarding wind turbines, wind turbine blades, acoustics involved with wind turbines, and previous research (touched upon in the Introduction) already conducted on the topic. The proposal then seeks to identify its goals, the methods for achieving these goals, any risk/safety concerns, any ethical concerns, the necessary resources and equipment, and a timeframe for the project. The main goal of this project is to effectively lower the acoustics given off by wind turbine blades by testing different biological airfoils and identifying any possible noise-reducing features.

Purpose

The long-term goal of the project is to use three different animal wings, penguin wings, pterodactyl wings, and bat wings to lower the sound pressure levels experienced by wind turbines without losing energy efficiency. The rationale is that the three following biological airfoils each have characteristics that could potentially improve the acoustics of wind turbine blades. First, penguin wings maneuver well in water, and could potentially provide greater amounts of power, especially in higher winds. Next, bat wings are generally quieter than bird wings, and pterodactyls are in the family of the largest animals to ever fly, and were optimal gliders that generated high amounts of lift. The work that is proposed here will seek to identify certain characteristics of each of these biological airfoils that can be applied to wind turbine blades. These characteristics will be beneficial in either decreasing the sound produced by the blades of a wind turbine and improving the power output of a wind turbine.

The main goals and intended goals are outlined in the specific aims below.

Specific Aim 1: Choosing biological model airfoils.

Specific Aim 2: Conduct initial/proof of concept testing at one constant windspeed while looking for optimal sound and power generation.

Specific Aim 3: Testing the models at different wind speeds.

The expected outcome of this work is to determine if any characteristics of penguin wings, pterodactyl wings, and bat wings are beneficial for wind turbine blades. Beneficial characteristics would entail lower sound power levels produced by wind turbine blades and increased power generation. Finally, it is expected that a certain windspeed will be found that is optimal in power and sound production for each type of blade.

Section III: Project Goals and Methodology

Relevance/Significance

Relevance to Global Warming

Global warming and climate change are significant issues posing many problems across the globe. The continuous burning of fossil fuels causes the amount of greenhouse gasses to increase, being the main factor behind global warming. The pollutants released by fossil fuels are also a factor in various medical-related issues and are prominently found in developing children. Issues include intellectual issues, behavioral problems, and different terminal illnesses (Perera, 2017). Other environmental issues include sea levels rising, extreme weather events growing in intensity, as well as interruptions in food supplies because of changing weather patterns (Rocha et al., 2022).

Wind Turbine Relevance

Wind turbines are an alternative source of clean renewable energy and are part of the solution to global warming by reducing emissions. One negative side effect of wind turbines is the sound they give off, which can disrupt local ecosystems, and are also disruptive to surrounding communities. As a result, limitations are placed on where wind turbines can be installed, as well as both the number and size of the wind turbines based on the sound pressure levels in nearby neighborhoods (Hoen et al., 2023). Therefore, the maximum capability of wind turbines to produce clean energy is hindered by these regulations.

Innovation

This project has multiple factors contributing to the overall innovation. Typically, studies will look at individual or a several characteristics to develop a modified bionic airfoil. As this project can’t use actual wings from these different animals or record their flights themselves, it seeks to do the next best thing by taking 3D models of the wings and using these as the wind turbine blades. Next, while owls have commonly been studied to reduce the overall acoustics of airfoils, this project includes two types of wings that haven’t been used regarding airfoil acoustics, penguin and pterodactyl wings. Finally, this project will conduct tests comparing these different wings/blades under constant wind speeds, configuration to the hub, and length. As a control, the length of the blades was scaled to be the same. Finally, this experiment will test each blade under identical changing wind speeds to identify the optimal wind speed that each blade functions at in terms of power and noise generation, and these will be compared amongst each other.

Methodology

Specific Aim #1: Conduct Proof of Concept Tests

The objective is to lower the amount of sound given off by wind turbine blades and effectively measure the sound power levels at a set distance from the apparatus. Proof of concept tests will include an initial construction of basic models, as well as methods to approximate the sound and energy produced.

Proof of Concept Methods. For proof-of-concept testing, a fan, axle, stand, and the 3D-printed hub with the attached blades will be used. A hole slightly larger than the axle will be drilled in the center of the 3D-printed hub. The axle will be placed through the hub, allowing the propellor section of the apparatus to rotate freely. The apparatus will be placed 3 feet in front of a fan that is blowing wind at a constant power setting. Four Vernier microphones connected to the Vernier Lab Quest device will be placed 6 inches around the apparatus. The Vernier Lab Quest device records the sound pressure levels in decibels (dB). The apparatus will then be removed and the sound of the fan itself will be recorded before the wind interacts with the apparatus. The apparatus will be placed back into its original location, and the fan will play at the same speed. The sound pressure levels will be recorded with the apparatus in place and the difference in the average sound pressure levels. This sound measurement will be the sound produced by the wind turbine apparatus. The rationale for this approach is to find the sound pressure levels with the microphones in the same position without the apparatus to record the average sound produced by the fan alone. Once the sound measurement with the apparatus is recorded, the difference in average sound pressure levels can be taken, giving the sound produced solely by the apparatus. Revolutions per minute (RPM) will be measured with a photogate to approximate power. The photogate will be set so it measures the number of times the propellor makes a revolution while accounting for it having three blades.

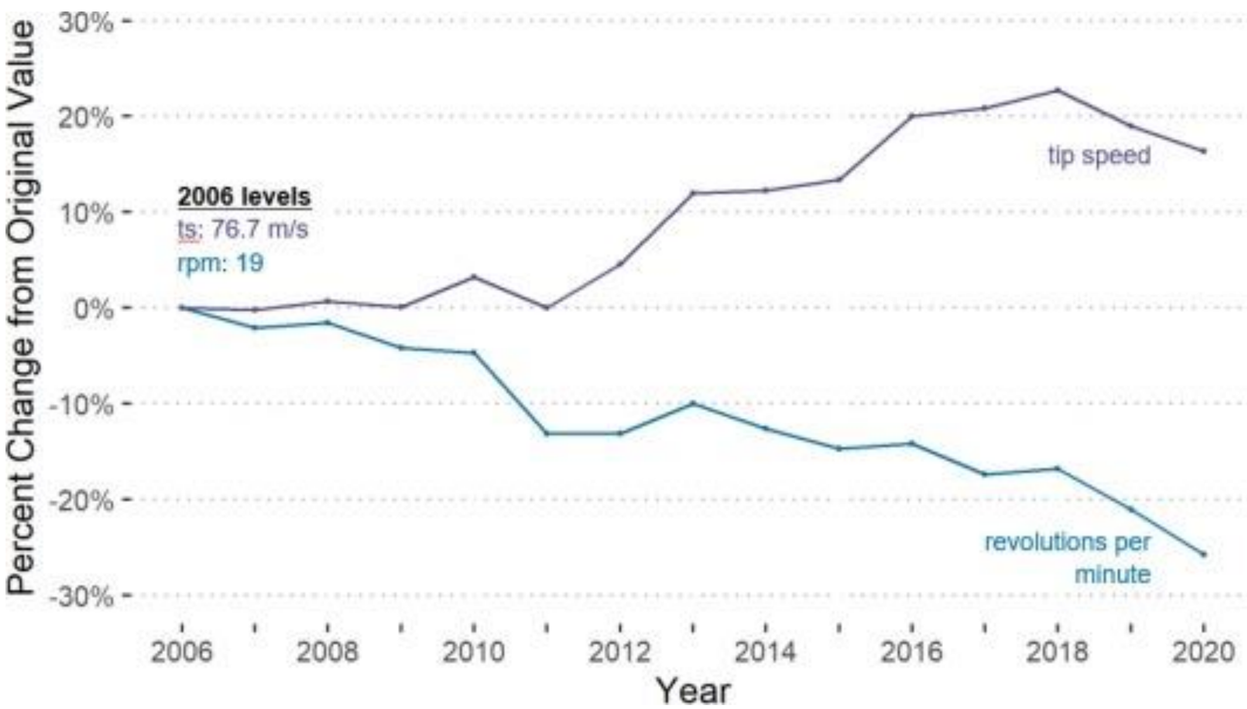

Figure 2: Graph of the Annual U.S. Fleetwide Tip speed (m/s) and Revolutions Per Minute (Hoen et al., 2023)

Justification and Feasibility. As shown in Figure 2, the average revolutions per minute (RPM) of wind turbines in the U.S. has been declining over the past 20 years. There is a relationship between revolutions per minute and the speed of the blades and, therefore, the amount of power that is generated. Figure 2 provides the context as to why power is related to revolutions per minute in the proof-of-concept testing. The reason blade tip speed is declining is due to the increase in the length of wind turbine blades, causing more sound to be produced. To offset the increase in tip speed due to longer blades, the rotational speed of wind turbines has been decreased, therefore the RPM has decreased (Hoen et al., 2023).

Expected Outcomes. The overall expected outcome of this aim is to measure the average sound pressure levels of the apparatus from a given distance and measure the revolutions per minute of the blades. Then, a comparison of sound and power generation for each model will be enabled.

Potential Pitfalls and Alternative Strategies. We expect there to be initial issues and outside sound interference. As a result, several trials will be taken to mitigate this risk. There may also be errors in the propellor designs, resulting in multiple iterations produced.

Specific Aim #2: Determine What Biological Models to Use as Wind Turbine Blades

The objective is to find different airfoil structures to reduce sound production and increase efficiency. The methods used to choose 3 biological models are as follows. First, research was conducted on prior studies, including what animals have been used most frequently for airfoil noise reduction, mainly owls (Wang et al., 2019). After determining what previous research had been done, searching for different methods of testing those airfoils, or finding other biological models that showed some promise but hadn't been researched for the specific purpose of noise reduction. Penguin wings, pterodactyl wings, and bat wings were chosen as the three biological airfoils.

Justification and Feasibility. Penguin wings perform optimally in water, a denser fluid than air. While penguins are flightless, their wings are highly specialized for swimming. Penguins have undergone different adaptations from typical bird wings, converting them to better suit their given environment underwater. Some of these adaptations include reduced feather sizes and barbules that have an increase in thickness. Overall size adaptations have made these wings shorter and firmer, converting the purpose to propulsion in water, and making the wing like a paddle (Louw, 1992). The increase in power enables penguins to move quickly through the water, allowing them to catch food and escape from predators. As a wind turbine blade, the penguin wing could potentially generate more energy, especially in high winds, as they interact with greater amounts of force because they operate in water.

Pterodactyls were a subgroup of the family pterosaurs. Therefore, pterodactyls were related to the largest animals to have ever flown. These include the Quetzalcoatl and Montanazhdarcho, the two largest animals to have ever flown (Britannica, 2023). While the acoustic performance and other characteristics of these animals' wings can never be exactly known, data from archeologists' 3D models can provide insight into knowledge that was gained from other fields. Pterodactyls' wingspan ranged from 20 inches to 3.3 feet, making them smaller relative to these other pterosaurs. However, the wing characteristics of these different species were similar, including their use of skin as a membrane for the wings instead of feathers. Boonman et al. found in 2020 that the feather noise contributed roughly 1/16th to 1/18th of the total amplitude of the sound created by the wingbeat of a Little Burn. Their study finds that feathers contribute to the overall noise created by birds flying. Recent evidence of soft tissue in pterodactyl wings was found, suggesting they had wing root fairings, which would aid in the overall force generated upon each wing stroke (Pittman et al., 2021). Due to the availability of 3D models, scaling factors, pterodactyl wings, and the optimal gliding performance possessed by pterosaurs, pterodactyls were the best option, representing these larger pterosaurs at a scaled-down size (Britannica, 2023).

Species	**Weight (g)**	**Wing length (mm)**	**Surface area (cm2)**	**dB SPL @1 m rec > 50 cm**	**Furthest rec distance (cm)**	**AcousticWingbeat (Hz)**	**Real wingbeat (Hz)**
Pigeon	232	250	220	67.6	126	9.6	9.4
Myna	112	160	117	60.8	116	11.4	12.1
Bulbul	41	125	85	57.1	81	17.4	12.3
House sparrow	28.5	76	80	58.2	107	22.0	22.6
Eptesicus	18.6	130	49	44.2	61	17.0	14.8
Rhinopoma	28.4	160	78.5	50.7	66	10.5	10.8
Rousettus	168.5	220	167	59.5	142	8.2	8.3

Table 1: Sound Pressure Levels (SPL) in birds and bats at low flight speeds. (Boonman et al., 2020)

Bat wings are like pterodactyl wings in that they don't have feathers but rather the skin that makes a membrane. The table above shows data for low flight speeds of 3 different bird species and 3 different bat species. The data shows that, on average, bats were quieter than birds whose wings were of similar size (area and length) (Boonman et al., 2020). For this reason, bat wings are being used as the third set of biological airfoils.

Expected Outcomes. The overall outcome of this aim is to determine what biological models could be used to benefit wind turbine blades in noise generation and power output. The acquired knowledge will be used to develop models for testing. These tests will be used to possibly find a method of airfoil noise mitigation.

Potential Pitfalls and Alternative Strategies. We expect the models to be found not to be 100 % accurate, as they won't be able to encapsulate all features (including on the microscale) of these wings. For the pterodactyl and penguin wings, there also isn't a general understanding of the acoustics produced therefore they may prove to be ineffective.

Specific Aim #3: Optimal Wind Speed for Each Airfoil

The objective is to find the wind speed at which each airfoil produces the least amount of sound while generating the most amount of energy. After initial tests are conducted at one windspeed, the windspeed will gradually be increased by increments. If viable, this will be modeled in ANSYS modeling software, allowing more variables to be controlled, limiting error. However, final prototypes will be printed and tested with a fan. The methods for testing and construction will remain the same as the proof-of-concept testing.

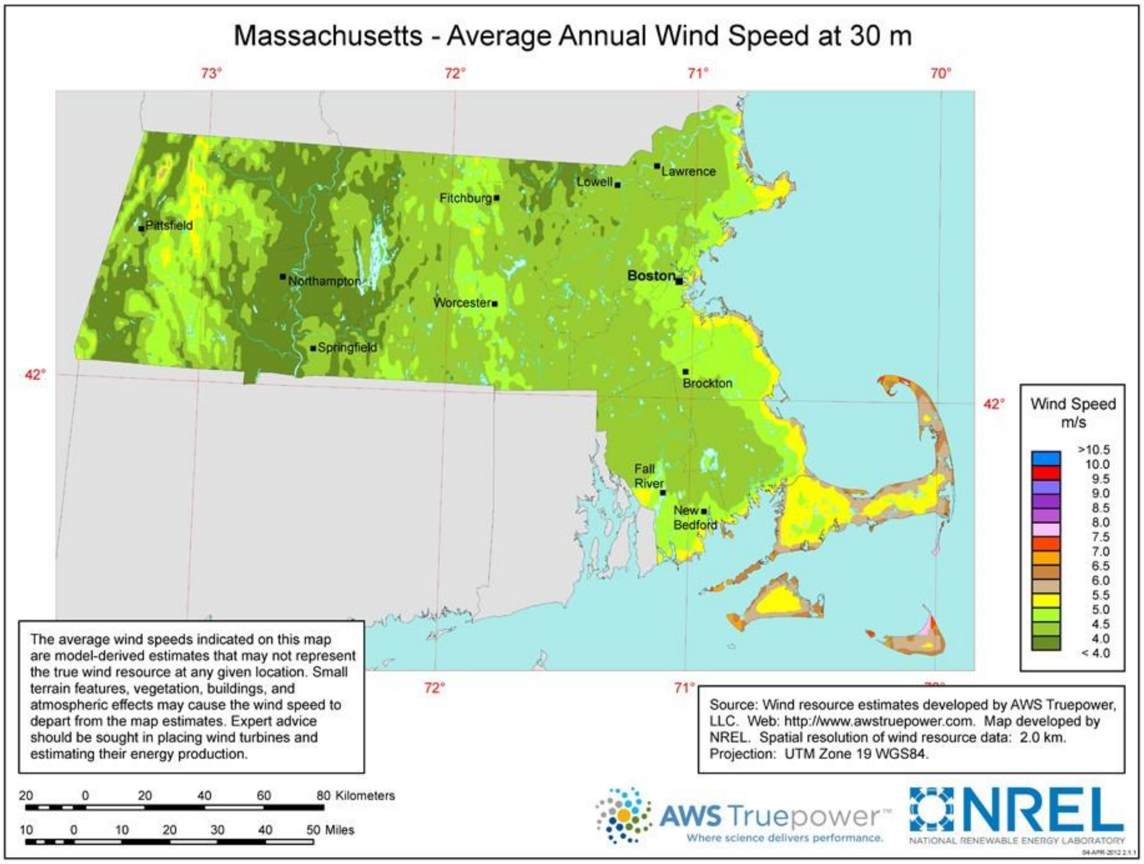

Figure 3: Map of the Average Wind Speeds in Massachusetts (WINDExchange).

Justification and Feasibility. Figure 2 depicts a map of the average wind speeds in Massachusetts (WINDEchcnage). This map serves as a visual representation of how wind speeds vary. Therefore, the optimal wind speed for each blade type can correspond to different locations. As a result, based on what rate ach blade produces the most energy and the least amount of sound, the corresponding blade characteristics would be better suited for areas with that optimal wind speed for an average.

Expected Outcomes. The overall outcome of this aim is to determine at what windspeed a certain blade produces the most energy and at what wind speed a certain blade produces the least amount of noise. Then, an optimal combination of the two based on a given location could be determined.

Potential Pitfalls and Alternative Strategies. As only 3 wind speeds will be tested, the optimal wind speed may be different than the tested wind speeds. The result would be the true potential of a certain blade not being known, affecting the results, analysis, and overall conclusion of this project.

Section III: Resources/Equipment

Software/Apps

ANYSYS Multiphysics modeling software may be needed if simulations are conducted virtually. COMSOL Multiphysics may also be needed to construct models that can be transferred into ANSYS. Tinker CAD will be used to construct the 3D propellor section of the wind turbine. The Vernier Graphical Analysis app will be used to track the photogate's information.

Physical Testing Equipment

A fan, 3D printer, potentially (screw, 6 nuts, 8 washers, Phillips head screwdriver, metal sheets) 2015 MacBook Air, Vernier Photogate, stand, and computer will be used to conduct physical tests. Pre-existing 3D models of penguin wings, pterodactyl wings, and bat wings will also be attached to a hub in Tinker CAD, creating the propellor section of the apparatus to be printed.

Section V: Ethical Considerations

Effect on Society

The research being conducted will have a positive impact on society. If successful, this project will introduce new methods of noise mitigation, aiding in the silence of wind turbines. Some constraints that were placed upon wind turbines will be lifted, allowing more wind turbines and larger wind turbines to be installed, as well as opening more locations where wind turbines can be installed. Overall, cleaner, renewable energy will be utilized, helping society turn away from fossil fuels. If this project isn’t successful, there are no negative implications, and others can pick up where this project leaves off or eliminate certain biological characteristics to mitigate wind turbine sound.

Potential Risks

The use of a wind tunnel (if used) will be under appropriate lab supervision. The wind tunnel is the only minorly dangerous method of this experiment.

Section VI: Timeline and Expenses

Timeline

Research began in August and will continue through January as more articles are read. The 3D design of the propellor sections for each different type of wing was started during the middle of November and will be concluded for pretesting by December 8th. Preliminary testing will begin the first weekend of December, Saturday the 2. It will continue through December 12th. Any adjustments to the models will be completed by the end of December. The main tests (for different wind speeds) will begin in late December and will be completed by the end of January. This entails physical testing with either a wind tunnel or fan, and (possibly) virtual simulation on ANSYS. Data analysis will be completed by the first week of February, and a conclusion will be completed by the middle of February. The entire project thesis paper will be completed in the first week of March.

Costs

Besides the potential cost of printing out higher-quality wings and the purchase of higher-quality 3D wing models, there are no additional costs for this experiment.

Section VII: Appendix

Section VIII: References

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