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The Blade Design of Wind Energy Turbines

Introduction

Due to rapid advancements in technology over the last century, the “global community” mentality becomes more relevant than ever in our society. The constant social connection through improving transportation methods, various media platforms and instant communication devices have become a modern day necessity. In order to keep up with the ever-increasing energy demand, civilisation has resorted to the exploitation of Earth’s resources. The extraction of finite resources such as coal, oil and natural gases is unsustainable and contributes greatly towards greenhouse gas emissions, leading us towards the current worldwide crisis of climate change. With the threat of climate change becoming unignorable, sources of renewable energy emerged as a solution, helping to provide long-term energy security while emitting little to no greenhouse gas emissions. Renewable energy sources include, hydroelectric power, solar power, tidal and wave power, but specifically wind power.

Technology has allowed the natural energy of the wind to be harnessed and applied into numerous functions. The earliest applications of wind energy include transportation (sailboats),the grinding of grain and water pumping, harnessed by the largest power source of its time: the windmill (Nelson, Vaughn. *Wind Energy : Renewable Energy and the Environment*. Energy and the Environment. Boca Raton : CRC Press, 2014.). With the amount of technology available today, the concept of the windmill has led to the creation of the wind turbine. The modern day wind turbine has the ability to convert the winds mechanical energy into electrical energy at highly efficient rates. The innovation of the wind turbine has become a major influence in our global fight against climate change by acting as a replacement for fossil fuels in energy production. Developed from a background of work on propellers, airplanes, and helicopters (Nelson, Vaughn. *Wind Energy : Renewable Energy and the Environment*. Energy and the Environment. Boca Raton : CRC Press, [2014], 2014.), blades are the most important feature of a wind turbine. The blade is a fundamental component of the structure of a wind turbine as it is responsible for extracting kinetic energy from the wind. Each aspect of wind turbine blades have been carefully designed, taking into account the configuration, material choice and structure, while providing the most effective solutions to common challenges.

Problems Surrounding the Development of Wind Turbine Blades

Despite all of the available information on large-scale blade design from the established backgrounds of propellers, airplanes and helicopters, the design process of wind turbine blades remains very difficult. There is a series of challenges associated with the design of blades for both large and small scale wind turbines, which is crucial to consider and ultimately overcome in order to produce an effective blade. Some wind turbine specific factors that must be addressed include blade fatigue, balancing blade strength with blade flexibility, finding a compromise between size and mass, and the cost and accessibility of the technology.

As wind energy technology improves, the scale at which the technology is applied increases as well. Certain turbine blades are operating at such a large scale that gravitational and inertial forces have started to have a greater impact on the blades than aerodynamic loads (Nijssen, Rogier P. L., Povl Bron̨dsted, and Woodhead Publishing Online. *Advances in Wind Turbine Blade Design and Materials*. Woodhead Publishing Series in Energy. Oxford: Woodhead Publishing, 2013.). With new dominant forces at play, the system of blades requires an analysis of more complexity. This stresses the importance choosing a material which reduces the blade weight while maintaining optimal size, in order to limit gravitational and inertial forces which can pose as a challenge. Not only is the weight to size ratio a concern for wind turbine blade designers, but finding a balance between strength and flexibility of the blade can arise as an issue. Industrial wind energy turbines are expected to withstand powerful and varying wind loads, as power in the wind increases as the cube of the wind speed (Nelson, Vaughn. *Wind Energy : Renewable Energy and the Environment*. Energy and the Environment. Boca Raton : CRC Press, [2014], 2014.). This requires a blade structure which is strong enough to operate throughout the highest of wind speeds, while being flexible enough to adapt to constantly changing conditions. It can be difficult to construct a blade that has the strength to provide sufficient structural stability while also being flexible enough to maximize energy production.

Structural fatigue is always a concern with wind energy technologies, but this can become a major problem particularly in turbine blades due to the extreme conditions of which they operate under. The powerful and varying winds that the blades are subjected to is damaging overtime, threatening the structural integrity and effectiveness of the technology. A blade on a wind turbine goes through more fatigue cycles in one year than airplane wings undergo in their lifetimes (Nelson, Vaughn. *Wind Energy : Renewable Energy and the Environment*. Energy and the Environment. Boca Raton : CRC Press, [2014], 2014). Ultimately structural fatigue is unavoidable, therefore it is important to limit it as much as possible to prevent a costly repair process. The removal/replacement process of the blades is timely and expensive, requiring numerous machines and transportation methods due to the size of the part. Not only is blade fatigue an expensive issue but it also disrupts energy production which stresses the importance of maximizing blade resilience.

The production and installation of a modern wind energy turbine is a costly process, which poses as a problem against the need for renewable energy sources. In order to promote the use of alternative energy sources, it is important that cost is taken into account throughout the design process. It remains a challenge for those involved in wind turbine design to find materials which are both inexpensive and accessible, while maintaining all of the structural properties required.

Considerations in Material Choice

As previously established, material choice is one of the most important factors in turbine blade design as it must meet a number of criteria in order to maximize efficiency. An ideal blade in a wind turbine would be lightweight, strong, flexible, resilient, inexpensive and accessible; factors which are all dependant on the material used. Finding a material which contains all of these qualities is a very difficult and controversial task, which is why research for the ideal material continues. It is for such reason that a wide range of materials which make up wind turbine blades exist in active use; including aluminum and other lightweight metals, beachwood, composites and the newly developed technology of biocomposites.

A composite in the application of wind turbine design is a material that is formed of either carbon glass or carbon fiber, mixed with epoxy resins (Shuwa, M., Ngala, G., & El-jummah, A. (2017). Investigating the Suitability of Selected Structural Material for the Blade of an Horizontal Axis Wind Turbine. *Arid Zone Journal Of Engineering, Technology And Environment, 13*(3), 315-324.). Due to composite materials relatively lightweight, strong and flexible structure, it becomes a feasible option for blade design and is popularly used amongst wind turbine designers. Though composites are structurally favourable in this application, they are expensive and not accessible to all regions. By using carbon glass and carbon fiber materials in the application of a renewable energy source, ultimately the effectiveness is defeated as they are neither recyclable or biodegradable (Shuwa, M., Ngala, G., & El-jummah, A. (2017). Investigating the Suitability of Selected Structural Material for the Blade of an Horizontal Axis Wind Turbine. *Arid Zone Journal Of Engineering, Technology And Environment, 13*(3), 315-324.). This results in the production of materials which have damaging consequences to the environment.

Both aluminum and beachwood are also commonly used in the design of wind turbine blades. Aluminum is a lightweight material which has the flexibility to adapt to the rapid and constantly changing wind intensities which are demanded of blades in this application, though lacks in terms of structural strength. Beachwood is characterized very similarly to aluminum and in both cases the blade size is limited due to both resources high elasticity (Shuwa, M., Ngala, G., & El-jummah, A. (2017). Investigating the Suitability of Selected Structural Material for the Blade of an Horizontal Axis Wind Turbine. *Arid Zone Journal Of Engineering, Technology And Environment, 13*(3), 315-324.).

As each of these materials fail to meet all of the standards that the ideal wind turbine blade upholds, there remains room for improvement in terms of material selection. Workers in this field continue to do research with the goal of developing new materials which improve the effectiveness of blades of wind turbines. The new technology of biocomposites is a direct result of sustainable engineering. Biocomposites are a hybrid form of typical composite materials, which replace the carbon and glass fibres with fibres that are derived from plants. The cellulose fibres extracted from various plants including flax, hemp, jute and bamboo are very strong relative to their low density composition (Nijssen, Rogier P. L., Povl Bron̨dsted, and Woodhead Publishing Online. 2013. *Advances in Wind Turbine Blade Design and Materials*. Woodhead Publishing Series in Energy. Oxford: Woodhead Publishing.). Biocomposites have the same beneficial characteristics of glass and carbon fibre composite materials, while having a lower impact on the environment; ultimately improving the sustainability of the renewable energy source.

Though there remains room for improvement in terms of turbine blade material selection, the variety of mediums available encourage the growth of wind energy turbines globally. The different advantages and disadvantages of each material allows for a diversified range of wind energy resources. Turbines blades can vary in both size, shape and configuration dependant on the type of material chosen.

Horizontal and Vertical Axis Wind Turbines

Before any major aspects of a wind turbine blade (such as shape, size and material) can undergo any form of a design process, it is essential that the general layout of the blades is determined prior. The blade configuration of wind turbines significantly impacts the design of the components that follow. As the placement and orientation of the blades is changed, the dynamic of the forces exerted on them is varied, which fundamentally will require different blade properties to optimize efficiency. The configuration of wind turbine blades is generally defined by the axis on which the blades rotate around, leading to two major arrangements; the Horizontal Axis Wind Turbine, and the Vertical Axis Wind Turbine (see Figure 1).

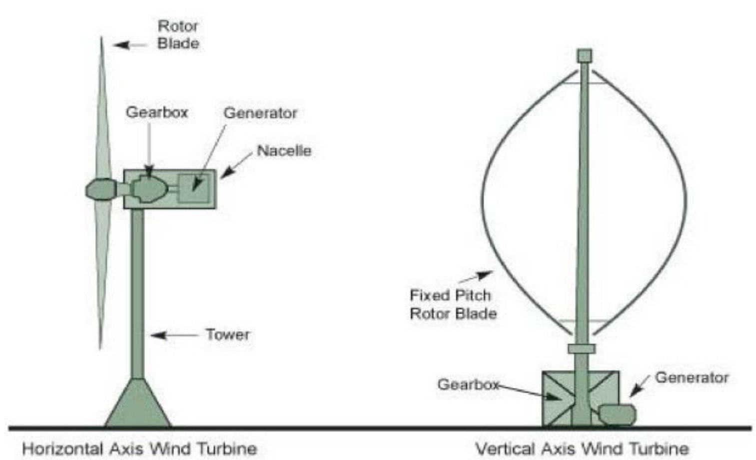

Figure 1

(Purohit, Pallav, and Axel Michaelowa. "Potential of Wind Power Projects under the Clean Development Mechanism in India." *Carbon Balance and Management* 2, no. 1 (2007). doi:10.1186/1750-0680-2-8.)

The Horizontal Axis Wind Turbine (HAWT) is the most common configuration for large scale wind turbines, and is the basis for the majority of research done in this exploration of wind turbine blade design. As suggested, a horizontal axis wind turbine operates using a varying number of blades attached along a horizontal axis. Using the rotational frequency of the turbines sweeping area, the number of blades used in a HAWT can then be determined specific to desired function and size. Using this concept, it is determined that as the number of blades increase, the lower the minimum wind speed and tip speed required to achieve maximum results ("The Performance Evaluation of Horizontal Axis Wind Turbine Torque and Mechanical Power Generation Affected by the Number of Blade." 2016. doi:10.1051/matecconf/20167003002.). With this being said, the rate of which the system improves relative to blade number also decreases as the number of blades increase. It is for this reason that modern and large scale HAWT's are generally designed with three blades, as it is the most effective design in terms of cost per blade and electric power generation ("The Performance Evaluation of Horizontal Axis Wind Turbine Torque and Mechanical Power Generation Affected by the Number of Blade." 2016. doi:10.1051/matecconf/20167003002.).

Though horizontal axis wind turbines are popular in the energy production industry, there remains some key problems with the overall design. A primary issue encountered is that at high wind speeds, a HAWT's operation may be stalled by reducing lift on its blades to limit power generation ("Increasing the Operational Capability of a Horizontal Axis Wind Turbine by Its Integration with a Vertical Axis Wind Turbine." *Applied Energy* 199 (August): 479–94. doi:DOI: 10.1016/j.apenergy.2017.04.070). This creates an inconsistency in power generation and wastes potential energy.

The blade number for a Vertical Axis Wind Turbine (VAWT) is determined using the same fundamental properties as HAWT's, though typically only uses two blades along the vertical axis. A VAWT can be used in the same application as a HAWT, though is often used on smaller scales. Due to their low-elevation location, vertical axis wind turbines lack access to the most powerful and effective wind streams, unlike the similar horizontal axis configuration. Located close to ground level, VAWT's experience powerful turbulence which can be a risk to the overall structural stability. Finally, as the blades of these turbines run along the vertical axis, the swept area of the blades is smaller resulting in less energy production.("Increasing the Operational Capability of a Horizontal Axis Wind Turbine by Its Integration with a Vertical Axis Wind Turbine." *Applied Energy* 199 (August): 479–94.doi:DOI:10.1016/j.apenergy.2017.04.070).

Both HAWT's and VAWT's have their advantages and disadvantages in the renewable energy industry, creating room in the market for the engineering of new products and technologies. Currently in the developmental stages is a newer wind turbine technology that mixes both horizontal and vertical axis configurations. This new design involves incorporating the strengths of both of the standard configurations. The end goal in creating this technology is to produce a more effective wind energy turbine, by minimizing the issues in HAWT's and VAWT's.

Analysing and Applying Aerodynamic Forces

The shape, size and curvature of a wind energy turbine blade is designed specifically according to the various forces that are going to be exerted on the device. Due to the vast amount and inconsistency of forces that is felt by the blade, the analysis of these aerodynamic forces becomes a very complex ordeal. Through the use of platforms such as the BEM (Blade Element Momentum) Method, the calculations required can be done electronically which improves the quality and rate at which the blades can be designed. Amongst the complexity of the system, there remains multiple simple and fundamental aerodynamic forces such as lift, drag and moment that greatly impact the design of both horizontal and vertical axis turbine blades.

In all technology-based blades, from airplanes to helicopters, each use airfoils in order to achieve maximum aerodynamic performance. This does not exclude the blades of wind energy turbines, which use various types of airfoils in their designs. An airfoil has the ability to distribute the forces from airflow over its surface, which simply speaking, causes a pressure difference resulting in the rotation of the blade. Three fundamental aerodynamic coefficients that are consequently produced are lift, drag and moment. Lift is a force which acts perpendicular to the oncoming airflow and ultimately "lifts" the blade, causing rotation. Drag acts parallel to the airflow and resists the motion of the blades caused by friction between the airflow and the blades surface and friction due to the difference in pressure (Gaunaa, Mac, Joachim Heinz, and Witold Skrzypiński. "Toward an Engineering Model for the Aerodynamic Forces Acting on Wind Turbine Blades in Quasisteady Standstill and Blade Installation Situations." *Journal of Physics: Conference Series* 753 (2016): 022007. doi:10.1088/1742-6596/753/2/022007.).The moment that is produced is another term for torque, which is applied around the aerodynamic centre of the airfoil (See Figure 2).

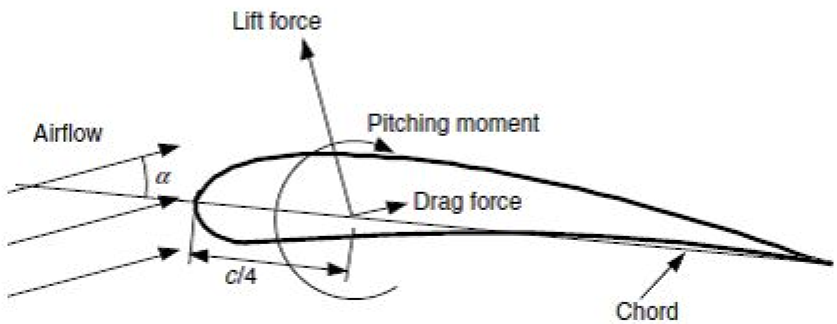

Figure 2

(Gaunaa, Mac, Joachim Heinz, and Witold Skrzypiński. "Toward an Engineering Model for the Aerodynamic Forces Acting on Wind Turbine Blades in Quasisteady Standstill and Blade Installation Situations." *Journal of Physics: Conference Series* 753 (2016): 022007. doi:10.1088/1742-6596/753/2/022007.)

An ideal HAWT blade focuses on creating high lift coefficients and fairly low drag coefficients in order to produce optimal results (Gaunaa, Mac, Joachim Heinz, and Witold Skrzypiński. "Toward an Engineering Model for the Aerodynamic Forces Acting on Wind Turbine Blades in Quasisteady Standstill and Blade Installation Situations." *Journal of Physics: Conference Series* 753 (2016): 022007. doi:10.1088/1742-6596/753/2/022007.). Along with these three basic aerodynamic concepts are a series of increasingly complex forces, all of which must be taken into consideration.

The Blade Element Momentum Method is a means used for calculating the complex forces, both aerodynamic and non-aerodynamic, exerted on wind turbine blades. As previously mentioned, gravitational and inertial forces begin to come into play with the increasing scale of the wind turbine blades. With forces of all strengths and dynamics in use, the BEM method can quickly analyse and present crucial data. The BEM method is the most commonly used platform of its kind and operates by dividing the blade model into discrete two-dimensional sections (Nijssen, Rogier P. L., Povl Bron¸dsted, and Woodhead Publishing Online. *Advances in Wind Turbine Blade Design and Materials*. Woodhead Publishing Series in Energy. Oxford: Woodhead Publishing, 2013.). From there, the individual aerodynamic forces on each discrete section can then be compiled and calculated as a whole.

Keeping in mind that it is important to increase lift and reduce drag in a turbine blade in order to maximize energy production, by using the BEM method analysis, adjustments to different aspects of the airfoil can be made where needed. The geometric conditions of an airfoil have a strong effect on the aerodynamic performance of a wind turbine blade, including the leading edge radius, mean camber line, maximum thickness and thickness distribution of the profile and the trailing edge angle (see Figure 3) (Gaunaa, Mac, Joachim Heinz, and Witold Skrzypiński. "Toward an Engineering Model for the Aerodynamic Forces Acting on Wind

Turbine Blades in Quasisteady Standstill and Blade Installation Situations." *Journal of Physics: Conference Series* 753 (2016): 022007. doi:10.1088/1742-6596/753/2/022007.).

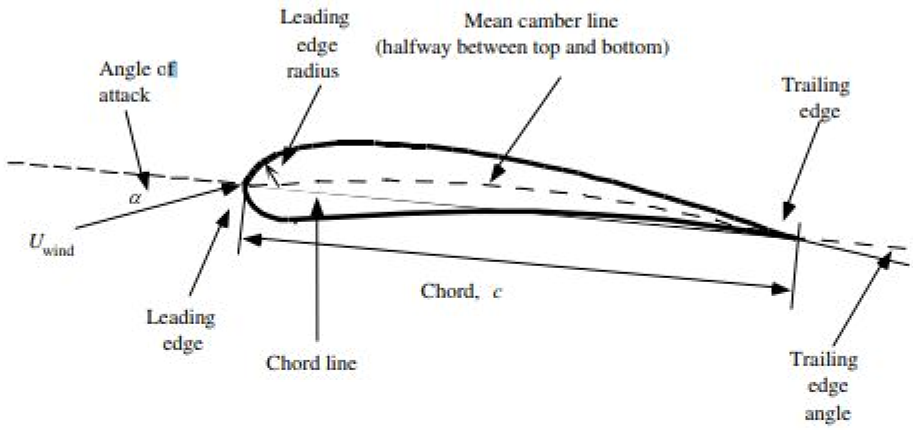

Figure 3

(Gaunaa, Mac, Joachim Heinz, and Witold Skrzypiński. "Toward an Engineering Model for the Aerodynamic Forces Acting on Wind Turbine Blades in Quasisteady Standstill and Blade Installation Situations." *Journal of Physics: Conference Series* 753 (2016): 022007. doi:10.1088/1742-6596/753/2/022007.)

By adjusting the different aspects of the airfoil following the analysis given of the BEM method, the optimal wind turbine blade with consideration to aerodynamic forces can be developed.

Conclusion

As the blades are the most significant components to the system of a wind energy turbine, it is important that every aspect of its design is carefully and purposefully planned. Starting with configuration to the materials being used to the shape of the blade, each stage of the design process is looking to improve upon or solve the problems associated with wind energy technologies. With the demand for wind energy increasing alongside the global effort to combat climate change, it is important to continue investing in renewable energy sources such as wind energy.

References

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Gaunaa, Mac, Joachim Heinz, and Witold Skrzypiński. "Toward an Engineering Model for the Aerodynamic Forces Acting on Wind Turbine Blades in Quasisteady Standstill and Blade Installation Situations." *Journal of Physics: Conference Series* 753 (2016): 022007. doi:10.1088/1742-6596/753/2/022007.