The Evolution of Rotor and Blade Design

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INTRODUCTION

The objective of this paper is to provide a historical perspective of the evolution of rotor and blade design during the last 20 years. This evolution is a balanced integration of economic, aerodynamic, structural dynamic, noise, and aesthetic considerations, which are known to be machine type and size dependent.

The resurgence of wind energy the last quarter of the past decade opened the door to a wide variety of rotor designs and materials that through trial and error, has converged to the market-driven, three-bladed composite, rotor configuration. The history behind this evolutionary process should be understood and documented to minimize unproductive regressions for future rotor designs.

The design of a modern rotor includes choices of blade number, airfoils, chord and twist distributions, and materials. The justification for each of these choices often includes conflicting considerations that need to be prioritized. For example, thin airfoils are desirable for their high lift-to-drag ratios and are roughness tolerant, whereas thick airfoils sacrifice some of these qualities to achieve the greater blade stiffness required for large machines. The pros and cons of these considerations are explored to better understand the current state of rotor and blade design. Some obvious blade design trends resulting from increased rotor size include lower blade solidity, increased airfoil thickness, and maximum lift coefficient, along with incremental increases in tip speed. Limits that govern these trends need to be understood in order to achieve a minimum cost-of-energy design.

WHERE WE STARTED

The rise of wind energy during the 1970s began with a trial-and-error process that included a wide variety of rotor configurations. The taxonomy of this decade included a variety of horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT) configurations. The HAWT’s included upwind and downwind configurations with various performance enhancers, such as diffusers and concentrators. The VAWTs included the lift-type Darrieus configuration and also the drag-type Savonius turbine. The evolution of wind turbines during the 1980’s was driven largely by the cost of energy, which resulted in the demise of many of the early concepts. Although VAWTs have the advantage of a drivetrain close to the ground for easy accessibility, their cost-effectiveness does not equal that of HAWT’s for reasons not fully documented. Aerodynamically, VAWT’s utilize less efficient symmetric airfoils than the higher lift-to-drag ratio, cambered airfoils used on HAWT’s. The constant chord, VAWT blades adversely affected blade efficiency and self-start capability. Rotor wake-induced losses of the VAWT’s are greater than those of HAWT’s since VAWT’s only operate at optimum lift-to-drag ratio over a small azimuth of the rotation. This leads to excessive wind energy going into rotor thrust loads rather than useful power output. The highly cyclic power and thrust generated by VAWT rotors also results in higher fatigue loads. In addition, the VAWT’s lack of a characteristic tower eliminates most of the additional energy available higher up due to wind shear. In comparison to a HAWT, a VAWT also tends to be a lower-rpm machine that derives power more from torque than rpm, which results in greater machine weight and cost.

For HAWT’s, almost all the performance enhancers resulted in greater cost than does a modest increase in blade radius to achieve the same energy improvement. Most performance enhancers, such as circular concentrators and diffusers, made it difficult to cost effectively address the hurricane design load condition. Cost considerations also resulted in the popularity of the two- and three-bladed rotor configurations.[1] The two-bladed rotor configuration provides lower cost but more complicated dynamics, which adversely affects reliability.

WHERE WE ARE

Additional criteria not always acknowledged within the industry, such as reliability, noise, and aesthetic considerations, narrowed the HAWT configurations further in the 1990s. Based on these criteria, the configuration of choice by the wind industry the last several years has been the upwind, three-bladed rotor. The moderate-size, lightweight, two-bladed teetering rotors, which lend themselves to tilt-down towers, may still, however, find a niche market in areas where installation cranes are unavailable.

Aerodynamics

Blade Number

For large commercial machines, the upwind, three-bladed rotor is the industry-accepted configuration. Virtually all large machines installed during the last several years are of this configuration. The three-bladed rotor offers the following advantages over the two-bladed configuration. Although the upwind choice is based largely on noise considerations, it also results in lower blade fatigue. Tower-shadow noise and impulsive blade loading for an upwind rotor, are less than for a downwind rotor that passes through the tower wake. For an upwind rotor, the blade-number choice is then a balance among blade stiffness for tower clearance, aerodynamic efficiency, and tower-shadow impulsive noise. The three-bladed rotor configuration appears to provide the best balance.

For a given radius and airfoil thickness, more blades result in lower blade flap stiffness. With three blades, adequate flap stiffness is still achievable to avoid tower strikes and the blade loading is low enough to avoid annoying impulsive noise. Aerodynamic efficiency increases with increasing blade number[2] with diminishing return (see Figure 1). Increasing the number of blades from one to two results in a six-percent increase in aerodynamic efficiency, whereas increasing the number from two to three yields only an additional three-percent. Further increases in blade number sacrifice too much blade stiffness for a minimal increase in aerodynamic efficiency. For small machines, the aerodynamic-efficiency increase resulting from more blades for a constant solidity rotor is diminished somewhat by the lower Reynolds numbers.

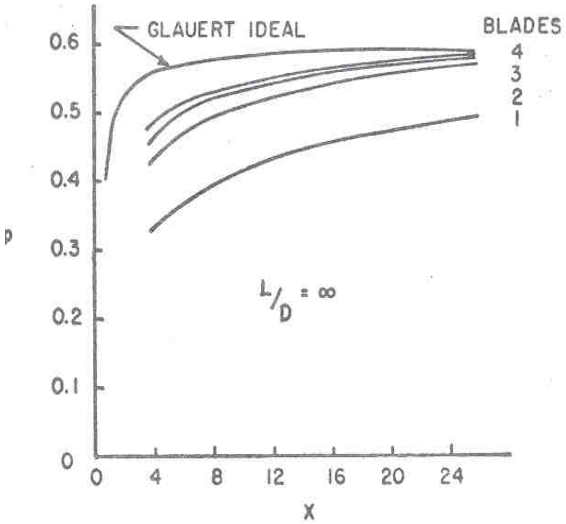

Figure 1. Aerodynamic efficiency versus tip-speed ratio as affected by blade number (Rohrback et. al.[2]).

Rotor-noise and aesthetic considerations strongly support the choice of three blades rather than two or one. A three-bladed rotor has two noise-related advantages over fewer blades. For a given rotor diameter and solidity, a three-bladed rotor will have two-thirds the blade loading of a two-bladed rotor and one-third that of a one-bladed rotor. As a result, a three-bladed rotor will have lower impulsive noise resulting from blade loading for either a downwind or upwind tower shadow. In addition, even for a given noise intensity at a fixed rotor rpm, the three-per-rev sound is less annoying than the two-per-rev sound. To compensate for the lower aerodynamic efficiency, one- and two-bladed rotors also tend to have lower solidity and higher tip speeds for a given diameter or power relative to three-bladed rotors. The higher tip speed leads to an increase in rotor noise, which is proportional to the fifth power of the tip speed. Most people also find the three-bladed rotor more pleasing aesthetically than a one- or two-bladed rotor. This relates to the more annoying “flicker effect” of fewer blades. The two-bladed rotor is perceived to rotate with an intermittent motion in contrast to a more continuous motion for the three-bladed turbine.

Another consideration that favors three blades is a more dynamically balanced rotor. As a result of the 120-degree spacing between the blades, rotor dynamics are more benign than for the 180- and 360-degree spacing associated with two- and one-bladed rotor systems, respectively. In addition, two-bladed rotors are more sensitive to one-per-rev, rotor mass-imbalance vibration. The more benign rotor dynamics of a three-bladed rotor tend to result in lower operating and maintenance cost.

Airfoils

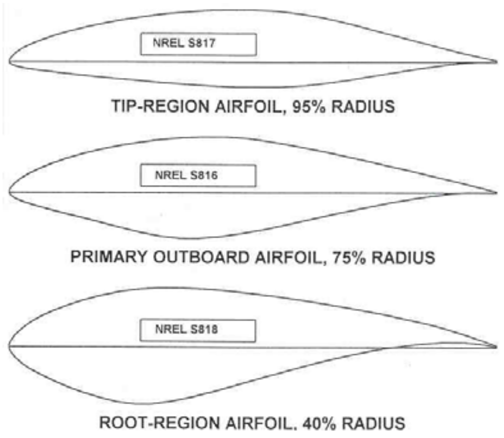

Figure. 2. Advanced airfoil family.

Airfoils have has been one of the more confusing and misunderstood aspects of designing a wind turbine blade. Performance characteristics and thickness desirable for airplane airfoils are not necessarily good for wind turbine airfoils. Both general aviation and wind-turbine airfoils do, however, benefit from extensive laminar flow and the associated low drag. Experience with commercial wind turbines during the 1980s identified most of the undesirable performance characteristics associated with NACA 44XX, 230XX, 63XXX, and NASA LS series airfoils. The NACA airfoils were developed prior to World War II, the LS(1) series, in the early 1970s. All these airfoils were developed for high Reynolds numbers and suffer from significant laminar separation bubbles when used on wind turbines at much lower Reynolds numbers. These bubbles can lead to large variations in airfoil performance as a function of roughness. These airfoils also lack adequate thickness for the blade-root region to address the structural requirement of high flap stiffness for tower clearance and efficient material use to accommodate high root-bending moments. Another characteristic needed for wind turbine airfoils is minimal sensitivity of the maximum lift coefficient to roughness effects. This is particularly important for stall-regulated wind turbines. Designing for roughness insensitivity only became possible through the use of modern airfoil design codes[3] by veteran airfoil designers. Recently designed airfoil families for wind turbines exhibit turbulent flow along the entire upper surface just prior to maximum lift. An example of this design philosophy is shown in Figure 2 for an airfoil family designed for large blades.

During the 1980s, excessive peak power was another significant problem for fixed-pitch, stall-regulated turbines that resulted in high drivetrain loads and generator failures. An unsatisfactory solution to this problem was to pitch the blades more toward stall, which controlled peak power at the expense of higher mean blade loads and wake-induced losses and lower rotor efficiency.[4] A more constructive approach employed NREL low-maximum-lift tip airfoils for passively controlling peak power while actually increasing overall performance.[5,6,7]

Further lessons concerning desirable airfoil characteristics[8] were learned in the 1990s. Desirable airfoil characteristics were found to be machine type and blade size dependent. Small- to medium-size, stall-regulated machines benefit from the use of low-maximum-lift coefficient (1.0 to 1.2) airfoils toward the tip to mitigate peak power. For very large machines, blade weight and cost increase faster than energy output. Weight and cost have been found to increase proportional to the radius to the 2.4 power, whereas energy output increases proportional to the radius to the 2.0 power. Based on this trend, large machines need airfoils of greater thickness and higher maximum lift to minimize blade weight and cost. For constant-speed machines, particularly stall-regulated ones, there is a price to pay since roughness sensitivity increases with airfoil thickness and stall characteristics deteriorate with increasing maximum lift coefficient. These undesirable effects are minimized with variable-speed machines.

For small machines, high maximum lift is not important. Low-maximum-lift, tip-region airfoils provide a gentle stall and the attendant increase in blade solidity has a negligible effect on blade cost. Although thin airfoils can be used on small machines, for variable-speed machines that furl to control peak power, thick airfoils are preferred to avoid tower strikes and blade flutter at high yaw rates and high rpm, respectively. The airfoils for small machines must be designed for low Reynolds numbers to avoid significant laminar separation bubbles that result in excessive drag, inconsistent maximum lift, and noise.

Blade Geometry

Minimum cost of energy is the criterion now used to optimize blade geometry rather than maximum annual energy production. To optimize on minimum cost of energy requires a multi-disciplinary method that includes an aerodynamic model, a structural model for the blades, along with cost models for the blades and all the major wind turbine components.[9,10,11] The blade design process also becomes multi-objective relative to the machine and the wind site. An example would be the design of a blade, for a given peak power, with a given mean wind speed, having a constraint on the maximum root-bending moment. For very large machines, cost-of-energy optimization normally results in a blade with less solidity than if it were optimized for maximum annual energy. Minimum cost of energy also benefits from higher rotor speeds, which are constrained by noise considerations.

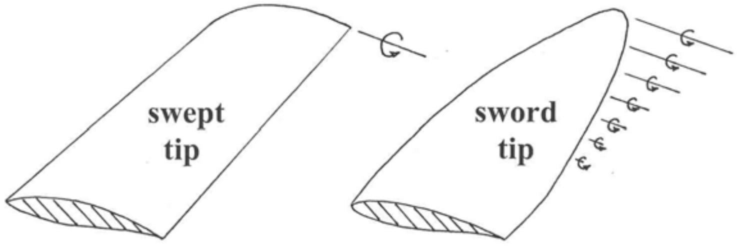

Figure 3. Blade tip geometries.

The blade geometry determined with the aerodynamic models does not provide guidance for an aerodynamic efficient tip shape. Test experience has shown that rounding the leading-edge corner with a contoured, streamwise edge (swept tip) yields good performance (see Figure 3). Tip shapes of other geometry (sword tip) are generally chosen for low noise at the expense of a reduction in performance.

Rotor Noise

Greater use of both small and large wind turbines worldwide has lead to greater emphasis on minimizing their environmental impact, particularly noise pollution. For large turbines, the two most objectionable rotor-noise sources have been pure tone noise[12] and infra-sound noise.[13] Pure-tone noise sources can be addressed through the design of the blade, whereas infra-sound noise is associated with large downwind machines and is inversely proportional to the number of blades.

Pure-tone noise sources are typically associated with the blade-tip geometry and sometimes with the airfoil shape. A tip geometry that generates a strong tip vortex, which then interacts with a thick trailing edge, gives rise to a pure-tone noise at around 2000 Hz. This noise can easily be eliminated for the swept-tip geometry, shown in Figure 3, using a sharp local trailing edge. Other tips that sweep the trailing edge forward reduce noise by diffusing the tip vortex, which normally increases tip drag. Airfoil shape generated pure-tone noise can result from the presence of significant laminar separation bubbles interacting with the trailing edge. The occurrence of this noise is more prevalent on small turbines, which operate at low Reynolds numbers.

Structures

Materials

During the past 20 years, large wind turbine blades have been fabricated from steel, aluminum, and composite materials such as wood, fiberglass, and carbon fibers. For a given blade strength and stiffness, the blade should be as light as possible to minimize inertial and gyroscopic loads, which contribute to blade fatigue. Blades made from steel and aluminum suffer from excessive weight and low fatigue life relative to modern composites.[14] Because of these limitations, during the past 10 years almost all blades have been fabricated from composite materials, usually fiberglass. Although carbon fiber provides the highest strength-to-weight ratio and stiffness, it has not been widely used because of its high cost, strain incompatibility when used with fiberglass, and handling difficulties. Common resin systems used in composite materials have included polyester, vinyl-ester, and epoxy. Polyester and vinyl-ester have been most widely used because of their lower cost. More manufacturers are switching to epoxy, however, to achieve better material properties. Epoxy alleviates shrinkage, does not become brittle with age, and provides better fatigue characteristics.

Structural Design

Many small turbines use solid blades milled from wood, either in one piece or laminated to avoid warpage over time. Other cost-effective approaches use fiberglass-reinforced composite material. An example is a pultruded blade embodying a solid cambered plate or a multi-cell airfoil. More recently, injection molding has also been used to fabricate small blades. This method involves injecting resin, such as polypropylene containing short glass fibers, into an aluminum mold of the blade geometry. Strength and thickness considerations for this method limit the blade length to less than two meters. This approach requires a large production volume to justify the high tooling costs. Most small blades are bolted directly to the hub plate with or without an outer plate. A root joint having an outer plate is the preferred approach because it provides two shear load paths and helps avoid submitting the bolts to high bending loads.

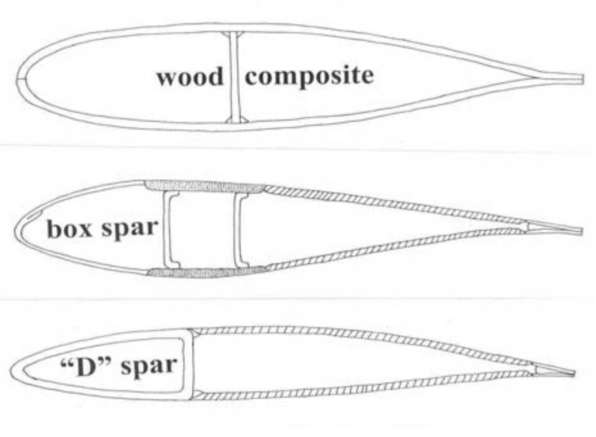

Figure 4. Large blade structural designs.

For large turbines, blade weight and cost become much more important. Larger blades mean lower rpm, less centrifugal stiffness, greater relative weight, and greater edgewise root-bending fatigue caused by the 1/rev gravity load. For large turbines, the edgewise root-bending load becomes a significant design load. To minimize weight, the small-turbine, solid-blade construction gives way to a lightweight, hollow blade design approach with one or more load paths. Several structural approaches for large blades are illustrated in Figure 4. A monocoque blade structure, such as used in the Gougeon blade, carries the entire load in the skin of the blade along a relatively linear load path. Although having the advantage of being lightweight with good buckling resistance, wood laminates do not lend themselves to compound curvature. This prohibits high root twist and large chord variations for better aerodynamic efficiency. Another common structural-design approach is to carry the majority of the load through a composite box beam or "D" spar with the remaining load carried in the skin of the blade. For megawatt size machines, higher inplane loads and a lower inplane natural frequency will require new structural designs to better address fatigue and dynamic excitation concerns. Cost savings may also be achieved by molding the outer blade region with upwind curvature to aid tower clearance.

A new structural design concern has emerged as a result of large-turbine installations throughout the western Great Plains. Storms with large hail have resulted in fiberglass skin damage and some separation of the leading-edge bond. Stopping the turbine with the blades in the plane of the rotor for minimum exposure to vertically falling hail can minimize skin damage. Blades having a seamless "D" spar or a bond line biased toward the pressure surface may be beneficial for eliminating the leading-edge bond separation.

Root Joint

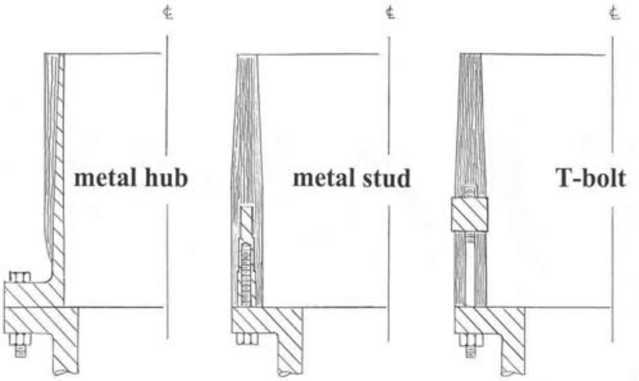

Figure 5. Large blade root designs.

A critical design region of any blade is the hub attachment. Blade-root joint designs used over the years have been strongly driven by cost, which typically represents 20% of the blade cost. Of the various hub types used in the 1980s, the tapered metal root cylinder hub has survived in various forms. Vestas, the largest manufacturer of wind turbines, fabricates their blades with an aluminum root cylinder. An example of this root design and other current design approaches are seen in Figure 5. Over the last several years, the embedded-metal-stud and T-bolt designs have become more popular in new blade designs. The metal stud root, which originated with the wood-composite blade, is now used with fiberglass blades. The metal-hub and metal-stud root joint result in the fiberglass being mainly in tension. For the T-bolt root joint, fiberglass inboard of the circular bolt is in compression while that outboard is in tension. Both the metal-stud and T-bolt designs have the advantage of using a larger blade-root diameter for a given hub flange diameter, which results in a more structurally efficient blade-root joint.

Soft Blades

Blades designed for low outboard flap stiffness, such as those on the Vestas 1.65-MW machine, help in alleviating flap and yaw-drive loads. A challenge when using this design approach on an upwind machine is to ensure adequate tower clearance, which is diminished over time as a result of composite-material creep. In addition to low flap stiffness, pultruded blades and those on the downwind, two-bladed Carter 300-kW machine have low torsional stiffness. Blades having low torsional stiffness become susceptible to flutter, particularly during rotor overspeed. To avoid flutter, the Carter blade is mass balanced in the chordwise direction. Mass balance is usually achieved by bonding lead into the leading edge to shift the chordwise center of gravity forward of the airfoil's aerodynamic center. The use of low torsional stiffness to achieve favorable flap/twist coupling has also intrigued researchers as a passive means of controlling peak power. Desirable coupling can be achieved through fiber orientation and by offsetting the blade pitch axis from the (quarter-chord) aerodynamic center. For most blades, the pitch and twist axes are positioned chordwise between the aerodynamic center and the airfoil's maximum thickness. Flap/pitch coupling is achieved without chordwise mass balance because the resulting strong tennis-racket moment would largely negate the desired coupling. Consequently, avoiding blade flutter during rotor overspeed is a concern.

Manufacturing Methods

Hand Lay-Up

Hand lay-up was the most popular manufacturing method for wind turbine blades through the 1980s. The cost of a typical composite blade using this approach was about 50 percent for labor and 50 percent for materials. Multiple fiberglass fabric layers were individually laid up by hand and coated with resin. This approach makes it difficult to achieve an optimum glass-to-resin ratio and reproducible blade weights. Fiber content was normally 60 percent or less by weight versus the desirable 70 percent. Drawbacks of this method include air pollution and undesirable working conditions resulting from the styrene outgasing as the polyester resin cures.

Filament Winding

The Kaman 40-kW and WTS4-MW machines used filament-wound 9.6-m and 38-m rotor blades, respectively. Although this technique results in strong blades with low labor cost, it also has disadvantages. Filament winding is an automated process whereby continuous strands of glass fiber pass through a resin bath and are then wound at an angle around a mandrel. The mandrel can be used to produce either an internal spar or the external blade shape. This process works well for fabricating a tubular or “D” spar. Concave blade surfaces, which result from airfoil camber or twist, do not lend themselves to filament winding. In addition, lightweight, non-extractable mandrel shells of the blade external geometry are needed for filament winding. Filament winding also results in a rough surface finish that is not compatible with good airfoil performance characteristics. Therefore, filament winding is best suited for interior tubular blade spars that are later molded into the blade.

Pultrusion

Lower blade costs, up to 50 percent, has been the chief promise of pultrusion.[15] The compromised aerodynamic and structural efficiencies, however, have been drawbacks that have limited its use for large blades. Pultruded blades do not lend themselves to nonlinear twist and tapered chord distributions. This leads to 12 percent lower aerodynamic efficiency. Although a large part of this loss can be eliminated by bonding on an inboard, twisted cuff and a tapered tip, any resulting cost-of-energy saving is then questionable. Secondary bonds may also affect the structural reliability of the blade. The greater flexibility of pultruded blades makes them undesirable for large, upwind commercial machines for which tower clearance is important. For increased flap stiffness and structural efficiency, external doublers must be added in the root region where the bending moment is greatest. Potential cost-of-energy savings with pultruded blades appear to be associated with downwind and small machines where machine reliability and survivability are more important than aerodynamic efficiency.

Resin-Transfer Molding

To reduce labor and resin cost, increase quality, and comply with air-pollution standards, the manufacture of blades using resin-transfer molding (RTM) was adopted during the past ten years. With this technique, the fiberglass layers are placed in the mold dry and covered with a membrane, which is sealed around the perimeter of the mold. A catalyzed resin is then introduced between the mold and the membrane under pressure, vacuum, or a combination of both. More consistent, higher quality parts having 70 percent fiber content by weight can be achieved. Reductions in labor cost and blade weight result in cost savings of 20 percent or more. Material properties are comparable to expensive prepreg fiberglass material cured in a heated autoclave. Volatile gases released as the part cures are contained rather than released to the atmosphere, creating an environmental hazard. These advantages point toward RTM as the manufacturing method of choice for future large wind turbine blades.

WHERE WE ARE GOING

The future will not likely see the wind-turbine evolutionary process deviate much from the current trend toward three-bladed, upwind rotors, which are rapidly maturing in design and construction. What can be expected is further refinement of the various configurations and further convergence toward the best of the three options of stall-regulated, variable-pitch, and variable-speed. Blades on large, stall-regulated machines with movable, overspeed-control tips are being replaced by variable-pitch blades for better peak-power control and reliability. Refinements are being directed toward improved structural designs, improved energy production with advanced control systems, power electronics, and airfoils. Higher-quality manufacturing methods are being developed that also result in lower blade cost. These refinements should contribute to reduced vibrations and loads, lower operating and maintenance costs, and the elimination of costly failures. The variable-speed approach has been gaining greater market acceptance and share each year.[16,17] Advantages such as greater aerodynamic efficiency, minimal sensitivity to turbulence and large coherent eddies, less aerodynamic noise, leading power factor, and lower tower top weight favor this approach. Future improvements in variable-speed generators and power electronics will one day yield greater overall efficiency than two-speed rotor operation. Further decreases in tower top weight are being pursued through the use of a more reliable, single-stage gearbox.

To support these turbine design trends, there will need to be an acceptable balance among the conflicting aerodynamic, structural, and noise considerations for future blade designs, in order to provide a low cost of energy. This balance has been found to be turbine size dependent, which puts greater emphasis on aerodynamic considerations, structural efficiency, and natural frequency placement with increased blade size. Large commercial blades will require thick, high-maximum-lift airfoils with consistent performance characteristics that are relatively insensitive to roughness effects, with low-noise tip shapes that do not adversely affect performance. RTM should provide a cost-effective, environmentally friendly manufacturing method that results in a high strength-to-weight ratio, fiberglass blade. The potential for further gains through stiffness tailoring and flap/twist coupling is being explored to better evaluate their effect on O&M costs and the resulting cost of energy.

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