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(54) Title: SPACER FOR WIND TURBINE ROTOR BLADE

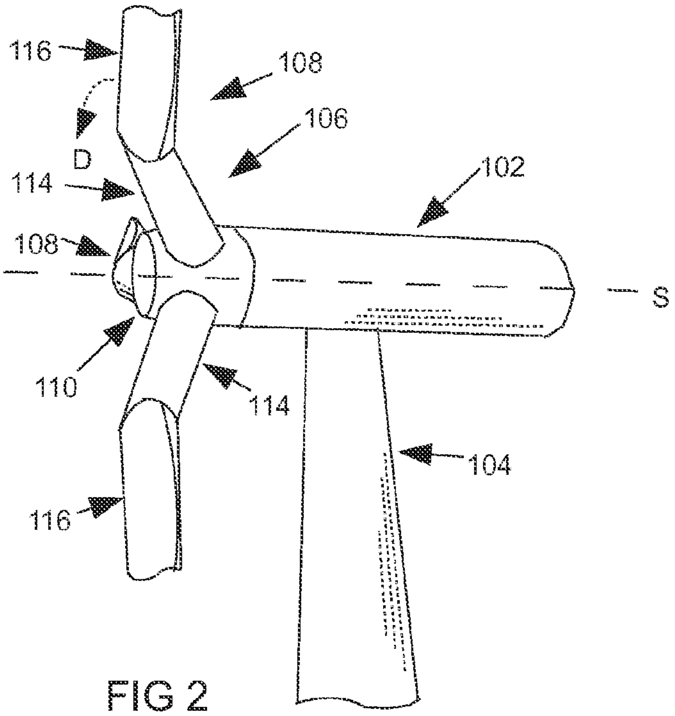

FIG 2

(57) Abstract: A forward running wind turbine includes a rotor having a hub and at least one blade adapted for attachment to said hub by means of a spacer, said spacer being adapted so as to provide a forward axial orientation of the spacer relative to a plane that is normal to the axis of rotation of the hub and aft axial orientation of the blade relative to a plane that is normal to the axis of rotation of the hub.

Declarations under Rule 4.17:

- *as to the identity of the inventor (Rule 4.17(i))*
- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*
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SPACER FOR WIND TURBINE ROTOR BLADE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims benefit of priority from United States Provisional application 62/122,091, filed October 11, 2014.

DESCRIPTION

BACKGROUND OF THE INVENTION

[0001] This invention relates to spacers for use with blades of wind turbine rotors, especially wind turbines of the front-runner or forward facing type, and to blades incorporating such spacers, the resulting rotors and to wind turbines utilizing such spacers, blades and/ or rotors, wherein the spacer possesses a forward cone angle and the remainder of the blade, or a majority thereof, has an aft cone angle.

[0002] Aft-running or downwind facing wind turbines wherein the blades describe a cone angle, that is, where the blade's structural axis is inclined at an acute angle with respect to the rotational axis of the rotor are known in the art. Examples include US-A-4,533,297, US-A-5,584,655, and US-B-7,530,785. Such blades are known to possess improved stability and experience reduced flutter and vibration under changing wind conditions. Disadvantageously, aft-running wind turbines experience excessive vibration and stress due to disruption of the wind by the wind turbine tower over the bottom portion of the rotor swept area. Scaling such turbines to large size, such as 5 or 10 MW of power generation, is extremely difficult due to this inherent design obstacle.

[0003] It is previously known in the art to provide a spacer that may be interposed between a wind turbine hub and a conventional blade to extend the diameter of the rotor thereby providing increased power production. In FR 2863318 the spacer or extender provides an acute angle terminus for mounting the blade so that the axis of the blade does not intersect the rotational axis of the wind turbine. The angle is inclined in the plane of rotation of the rotor. In WO 2003060319, the spacer is fixed to the rotor hub by means of a first flange and comprises a second flange for fixing the rotor blade thereto at an acute angle that opens away from the tower to provide increased clearance between the blade and tower under wind loads. Disadvantageously, angling the rotor blade forward over its entire working length, that is, using a forward cone angle in a front running wind turbine, makes the blade extremely unstable and subject to vibration and flutter.

[0004] Several designs for upwind turbine rotor blades including aft-swept outer regions are known. In one such design, referred to as an aeroelastic blade design, wind gusts striking a blade with aft sweep, give an increase in out-of-plane (flapwise) loading which produces a pitching moment about sections further inboard. This pitching moment acts to induce outer portions of the blade to twist the leading edge of the blade sections into the wind so as to reduce the aerodynamic angle of attack of those sections, thereby ameliorating peak transient loads that the blade would otherwise experience. However, if the base of the blade remains unswept or is swept aft, the pitching moment induced over the entire blade is reacted at the base of the blade through pitch drive hardware. For even modest sweep, this moment can overwhelm baseline aerodynamic pitching moments for which the pitch hardware is designed. In other words, although in-plane aft sweep of wind turbine rotor blades can be used to ameliorate transient loads, aft sweep also induces pitching moments at the blade base that can overwhelm the baseline aerodynamic pitching moments for which the pitch hardware is designed. In US-B-7,344,360 and US-B-8,757,982 to Wetzel et al., it is suggested that forward sweep in the base section of the blade can be employed to negate such pitching moment. Wetzel et al. further teach that forward sweep can also be introduced by the hub however, that would necessarily impose aerodynamic pitching moments onto the bearings and drives. In addition, modification of existing windmill hubs would entail large costs in order to adapt the rotors to accept such blades. In US-A-20130189116 to Obrecht et al., a blade of similar design to Wetzel et al. included a torsionally rigid base, an inboard section having forward sweep comprising up to 25% of the blade's length, and an outboard section having aft sweep. The disclosures of all of the forgoing references, or their English language equivalents, are hereby incorporated by reference for purposes of teaching techniques and concepts within the skill of the ordinary artisan.

[0005] Disadvantageously, prior art blade designs utilizing forward blade sweep in an inward section of the blade, or in the hub itself, to negate pitching moment induced by outboard blade sweep have met with only limited success. Within the confines of airfoil architecture, sweep, that is, the angle of departure between the elastic axis of a blade and its pitch axis, has only limited ability to change pitch moment acting on the blade base. Accordingly, excessive sections of inboard blade must be employed to introduce sufficient forward sweep to counter forces generated by outer blade aft sweep. For example, in Wetzel et al's design, the portion of the blade characterized by aft sweep is ideally located starting at approximately 60 percent of blade length. Moreover, both prior art designs necessarily rely on blade tip bending to reduce pitch moment. This results in undesirable vibration and flutter and blade flapping which can shorten blade life and cause catastrophic blade failure under extreme weather conditions.

[0006] Furthermore, prior art aeroelastic designs necessarily employ inboard portions of the rotor having a thrust generating aerodynamic design. Because the innermost regions of the rotor have only minimal rotational speed, highly nonsymmetrical lift producing airfoil designs are employed in the inner most regions of the rotor in order to generate maximum power output, ideal forward sweep of the rotor, and high strength and rigidity to such regions of the rotor. Consequently, these regions of the rotor are required to use a highly asymmetrical airfoil design to produce maximum thrust. These airfoil designs are prone to movement of the center of wind pressure with varying wind angle of attack and speed, resulting in the generation of undesired flutter or induced vibration under changing wind conditions. In addition, these inner regions of prior art blade designs generate excessive drag, resulting in a lessening of total aerodynamic efficiency. Finally, such airfoil designs employ thick forward cross sections coupled with relatively thin rear or following blade shapes, even those having a negative camber. This blade design has several disadvantages. The relatively thin, rear, negatively cambered sections are structurally weak and prone to breakage. Additionally, the relatively large, bulbous forward sections are prone to collection of dead, impacted insect bodies, resulting in loss of aerodynamic efficiency under actual use conditions, necessitating frequent expensive cleaning and repair service.

[0007] Finally, it should also be noted that prior art aeroelastic rotor blades are designed such that the outer blade sections bend under normal wind loads encountered during operation. The ability of such blade designs to withstand additional or excessive loads under non-standard wind conditions is accordingly limited. That is, under operational conditions, blade bending movement is more limited in the positive (downwind) direction than it is in the negative (upwind) direction. This results in an undesirable asymmetric blade response to changing wind conditions and in operation causes movement in the center of thrust which induces unwanted vibration in the blade.

[0008] It would be desirable to provide a blade spacer for use in wind turbines that achieves a reduction in pitching moment at the hub, but without some or all of the disadvantageous of prior art designs. It would also be desirable to provide a blade spacer for use in wind turbines that possesses improved structural and performance properties compared to prior art designs and/or results in improved performance, longevity or reduced cost to manufacture and use. It would also be desirable to provide a blade spacer for use in wind turbines that can operate under higher wind speeds than previous designs and/or is more resilient to rapidly changing wind speeds and directions, that is, gusty wind conditions. Finally, it would be desirable to provide a blade spacer for wind turbine blades resulting in rotors having lessened incidence of wildlife harm, especially reduced bird impact properties.

BRIEF DESCRIPTION OF THE INVENTION

[0009] Accordingly, in one aspect the present invention provides a blade spacer or mounting base adapted for use on a forward running wind turbine, said spacer being substantially rigid and adapted for attachment by it's proximal terminus to a wind turbine hub such that the alignment axis of the spacer is disposed at an acute forward angle relative to a plane that is normal to the axis of rotation of the hub (forward cone angle) and a distal terminus adapted for attachment to the base of a wind turbine blade such that the alignment axis of the blade is disposed at an aft acute angle relative to a plane that is normal to the axis of rotation of the hub (aft cone angle). As used herein the term "spacer" refers to the innermost section of a blade combination that is incapable of generating substantial amounts of lift or torque under operating conditions. Preferred spacers for use in combination with wind turbine blades herein do not possess a surface in the shape of an airfoil, excepting for purposes of drag reduction. Highly desirably they are incapable of generating more than 2 percent of total torque for the blade and spacer combination , more preferably, no more than 1 percent of total torque of the blade and spacer combination. By the term "substantially rigid" is meant that no deformation or delamination results from torque forces and bending moments encountered during operation according to design specifications and deflection, if any, is inconsequential under the same conditions.

[0010] In another aspect, the invention provides a blade spacer as previously disclosed, said blade spacer being capable of providing a forward orientation of the alignment axis of the spacer relative to the pitch axis of the hub to which the spacer is attached.

[0011] In still other aspects, the present invention provides a blade spacer according to the previous embodiments which, starting at a point inward from the distal terminus thereof, is curved, thereby forming a bend or knee to enable aft acute angle orientation of the turbine blade.

[0012] Still further, the present invention provides a blade spacer according to any of the previous embodiments additionally comprising a pitch control mechanism in the distal terminus thereof for adjusting the angle of attack of the blade.

[0013] In yet other aspects, the present invention provides a rotor for a wind turbine having a hub and at least one blade spacer according to any one of the present designs.

[0014] Additionally, the present invention provides a wind turbine that includes a rotor comprising a hub and at least one blade spacer according to any one of the present designs.

[0015] In a further aspect, the present invention provides a method for making a blade spacer for a wind turbine comprising determining a shape by selecting axial alignment angles, size and shape for the spacer, and sizes, shapes, axial alignments, and optional sweep angles for blades to be joined thereto so as to effectuate one or more of the following objectives: (a) decrease or eliminate shifts in centers of air pressure under varying air flow conditions experienced by the blade, (b) reduce or minimize negative effects on aerodynamics, especially reduce loads imposed onto the yaw control mechanism due to unstabilized blade design , (c) reduce or minimize pitching moment at the hub, especially under extreme weather conditions, and (d) maintain structural integrity and longevity under use conditions, and fabricating a blade spacer in accordance with the determined shape.

[0016] It will be appreciated that, when the blade spacers disclosed herein are axially aligned forward by the proper amount as explained herein, configurations of the present invention reduce or eliminate a pitching moment at the hub of the wind turbine resulting from rearward axial alignment and/or rearward sweep of the blade, and the aft aligned blade is inherently more aerodynamically stable.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. 1 is an illustrative drawing of an airfoil shape.

[0018] FIG. 2 is a partial perspective view of an exemplary configuration of a forward running wind turbine employing a spacer of the present invention.

[0019] FIGs. 3a, 3b and 3c are side view drawings of exemplary spacers of the present invention suitable for use in the wind turbine configuration represented in FIG. 2.

[0020] FIG. 4 is drawing of a blade in combination with a spacer of the present invention.

[0021] FIG. 5 is a drawing of a blade in combination with an alternative spacer configuration of the present invention.

[0022] FIG. 6 is a frontal view of an alternate embodiment of spacer and blade combination of the present invention having non-radial alignment of the blade.

[0023] FIG. 7 is a drawing of a preferred blade airfoil shape for use in a rotor according to the present invention.

[0024] FIG. 8 is a cross section drawing of one embodiment of blade for use in a rotor according to the present invention.

[0025] FIG. 9 is a partial front view of one embodiment of a rotor according to the present invention.

[0026] FIG. 10 is a top partial sectional view of a blade for use according to the invention comprising multiple segments.

[0027] FIG. 11 is a partial frontal view of a blade end for use in a further configuration of the present invention having improved aerodynamic properties.

[0028] FIG. 12 is partial perspective view of a blade end fitted with a fin in a further alternate embodiment of the present invention having improved aerodynamic properties.

[0029] FIG. 13 is a partial frontal view of the blade end of FIG. 12.

DETAILED DESCRIPTION OF THE INVENTION

[0030] As used herein the term “airfoil” refers to a closed curve, such as closed curve 100 depicted in FIG. 1, which represents the cross-sectional shape of an elongated surface (blade) designed to produce lift when in contact with moving air. Each airfoil shape likewise is elongated and the line connecting both extremities along the major dimension is referred to as the “chord”. The median points between two respective points of the airfoil closed curve (measured perpendicularly to the chord line) taken together form a curved segment called the “median line”, with terminal points that are the same as the terminal points of the chord. The working portion of a wind turbine blade comprises a series of such airfoil shaped cross-sections extending from the base to the tip or outer end of the blade, the set of mid-points of the median lines thereof defining it’s structural axis which is a line for a flat blade or a curve for a twisted or bent blade. As used herein the term “alignment axis” of the blade refers to a line defined by the innermost and outermost median line mid-points of the blade measured at full deflection under maximum operating conditions, the length of the blade being the distance between the innermost and outermost median line mid-points. The outer surface of the working blade is defined by the collection of curves from adjacent airfoil shaped cross-sections, the set of respective median lines of each airfoil shaped cross-section dividing said outer surface into two minor surfaces, a “high pressure” surface and a “low pressure” surface. Because airfoil shapes are often depicted with the chord arranged horizontally and the direction of wind proceeding relatively from left to right, the high pressure surface is often referred to as the “lower surface” and the low pressure surface is referred to as the “upper surface” regardless of the actual orientation of the working blade surfaces when in use.

[0031] When air moves over the surface of an airfoil-shaped body aerodynamic forces are produced. The component of this force perpendicular to the wind direction is called “lift”. The component parallel to the direction of wind motion is called “drag”. The component of lift experienced by the wind turbine blade in a direction that is perpendicular to the rotational axis of the turbine is referred to as “thrust”, and causes rotation of the wind turbine rotor which may be converted into useful work, especially generation of electrical energy. As wind moves past the blades with enough speed to generate sufficient lift to overcome inertial and drag forces, the rotor system rotates and the wind turbine converts the wind energy into electrical or mechanical energy for performing useful work. The skilled artisan will appreciate that closed curve 100 is merely one illustrative embodiment of a suitable airfoil shape for use in the present invention and not intended as a limitation thereon.

[0032] Referring to FIG. 2, a forward-running wind turbine 101 in some configurations comprises a nacelle 102 housing a generator and associated gearbox or alternative power transfer mechanism (not shown in FIG. 2). Nacelle 102 is mounted atop a tall tower 104, only a portion of which is shown in FIG. 2. Wind turbine 101 also comprises a rotor 106 that includes one or more combination blades 108 (partially shown) attached to a rotating hub 110 having rotational axis S. Most often, axis S is tilted up from horizontal from about 3 to 10 degrees, to lessen the effect of any bow wave emanating from the tower and to obtain more evenly balanced wind currents from top to bottom of the rotor's swept area since wind speeds close to ground level are often attenuated due to ground effect. The direction of rotation of rotating hub 110 is indicated by arc D which is usually clockwise viewed from the front. Although wind turbine 101 illustrated in FIG. 2 includes three combination blades 108, there are no specific limits on the number of rotor blades required by the present invention. The innermost portion of each combination blade, identified as 114, comprises the spacer. The outermost segment of combination blade 108 is identified as blade 116 (shown in partial view) and comprises a suitable airfoil shape designed to produce thrust that causes rotation of rotor 106. Ideally, blade 116 is a conventional wind turbine blade which is used or reused in combination with the present spacer to retrofit existing wind turbines in conformance with the present invention.

[0033] Nacelle 102, containing the rotor system, typically pivots about the vertical tower 104 to take advantage of wind from any direction. The pivoting about this vertical-axis is known as yaw or yaw response and the vertical-axis is commonly referred to as the yaw-axis. Effective yaw control of upwind horizontal axis wind turbines is highly desirable in order to position the rotor system properly relative to the mean wind direction. When a rotor system is not properly positioned with reference to the mean wind direction, the efficiency of the rotor system is significantly reduced. When an angle of separation develops between the mean wind direction and the axis of rotor rotation, the power output of the rotor system, and therefore of the turbine, decreases.

[0034] Various undepicted components of wind turbine 101 are housed in nacelle 102 and hub 110 atop tower 104. Examples include a generator, drive train, braking system, bearings, yaw control mechanism, wind speed sensors, pitch control mechanism, and so forth. In some configurations, one or more sensors and controllers comprise a control system used for overall system monitoring and control including pitch and speed regulation, high-speed shaft and yaw brake application, yaw and pump motor application and fault monitoring, electrical wave form modification and energy storage. Alternatively, distributed or centralized control architectures are used in some configurations. Hub 110 and combination blades 108 together comprise wind turbine rotor 106. Rotation of rotor 106 causes a generator to produce electrical power, generally through a power transfer mechanism such as a gear box. Desirably, main bearings are provided both in front of and behind hub 110 to support the entire rotor weight while in operation. Support for the forward bearing may be provided by a fixed quill (not depicted) supported from the main structural base of nacelle 102 and projecting through the center of hub 110 as is known in the art. The pitches of combination blades 108 can be controlled individually by pitch control mechanisms located within the hub 110 (not depicted). In some configurations of the invention depicted later, a pitch control mechanism located within the distal terminus of spacer 114 is employed to change the angle of attack or pitch of blade 116. Moreover, in one embodiment no pitch control mechanism is provided and combination blades 108 are fixed in spatial relation to hub 110. Yaw control of the nacelle 102 is employed for protection against over speeding of the generator and other mechanical parts. Because the present rotor design is more stable in high wind conditions than prior art configurations, the need for rapid pitch control of combination blade 108 is largely unnecessary, resulting in an improved, simpler, cheaper, and more reliable design, as well as lighter construction. Moreover, due to the inherently improved aerodynamic properties of rotors according to the present invention, wind turbines may be allowed to continue turning during high wind conditions, using yaw control and pitch control to limit rotational speeds, thereby extending operating ranges of the turbine.

[0035] Referring to FIG. 3a, in its simplest embodiment, the present invention comprises a spacer 114a having proximal terminus 201a adapted for attachment to the rotor hub and a distal terminus 202a adapted for attachment to the base of blade 116 thereby forming combination blade 108. The alignment axis A of the spacer is defined as a longitudinal line connecting the geometrical centers C1 and C2 of the proximal and distal terminal outer surfaces. The length of spacer 114 is the distance between respective geometrical centers of the outer faces of proximal terminus 201a and distal terminus 202a along line A. Although flanges are depicted in FIG. 3a for attachment to the rotor hub and blade 116 using, for example, bolts or other attachment means, it is to be understood that any suitable method of attaching both termini, such as interlocking clasps; a socket and corresponding fitment; stud bolts bonded, molded, or otherwise inserted into either the hub, spacer or blade base; or other suitable mechanism may be employed for joining the respective portions of the rotor, it only being requisite that both ends of spacer 114 are shaped or adapted for attachment so that when attached to the wind turbine hub the spacer's alignment axis is aligned forward relative to a plane that is normal to the axis of rotation of the hub thereby providing a forward cone angle for the spacer, and the blade's alignment axis is tilted aft relative to a plane that is also normal to the axis of rotation of the hub, thereby providing aft alignment for the blade. While some or all of said forward and reverse alignment angle may be due to orientation of the mounting fittings of the hub and/or blade, or by use of an adapter or union to join the spacer to the hub and/or blade at the appropriate angle, in a preferred embodiment at least some, and more preferably most, if not all, of the forward and/or reverse angle alignment is the result of orientation of the attachment face on each spacer end at a non-orthogonal angle to alignment axis A. Highly preferably, the reverse cone angle at the distal terminus is due, at least in part, to off-axis alignment between the structural axis of the innermost one percent length of blade 116 and alignment axis A. In US-B-7,517,194 and US-B-8,231,351, suitable attachment methods for joining blade segments or joining blade segments to rotor hubs, which may be used herein to join spacers and blades or hubs and spacers, are disclosed.

[0036] FIG 3b discloses an alternative embodiment of spacer 114b which tapers in cross-sectional size from proximal terminus 201b to distal terminus 202b. Tapering reduces the total mass of the spacer and is highly desirable for this reason. As one example, a spacer having circular cross-sectional shape may have a diameter at the proximal terminus of about 5 m while the diameter at or near the distal terminus may be about 4 m. In general, all joints or surface transitions on the spacer or joining the spacer with the hub or blade are chamfered, rounded, filleted, beveled or fairings are placed over any protruding or receding sections of various rotor components to improve aerodynamic performance.

[0037] FIG 3c discloses yet another embodiment illustrating spacer 114c having proximal terminus 201c fitted with numerous stud bolts 205c placed in a circular pattern and located near the circumference of proximal terminus 201c for attachment to a hub. A bend 112c in spacer 114c or in an adapter 206 attached to spacer 114c imparts aft axial alignment to a blade attached to distal terminus 202c. Alignment axis A includes the geometrical centers C1 and C2 of the proximal and distal terminal outer surfaces. The proximal and distal termini in general are shaped so that their end surfaces conform in size and shape to the corresponding attachment surface, that is, either the corresponding hub or blade face. The skilled artisan will appreciate that forward cone angle may be produced using spacers of the invention having proximal terminal surfaces disposed an angles other than 90 degrees to the alignment axis of the spacer, and/or by the presence of one or more longitudinal curves or bends in the spacer body. In addition, an adapter or coupling (not depicted) having the same curved or bent shape as 112c may be employed in combination with an otherwise straight spacer to provide the requisite distal terminal surface oriented with aft cone angle for mounting of the wind turbine blade.

[0038] In some configurations of the present invention and referring to FIGs. 4 and 5, combination blade 108 attached to hub 110 of a wind turbine comprise spacer 114 having alignment axis A oriented forward, that is up-wind, relative to a plane N normal to the axis of rotation S. An optional conventional pitch control mechanism (not depicted) is located within hub 110 and is attached to the base of spacer 114 to provide pitch control of combination blade 108 along conventional pitch axis P. Forward alignment as disclosed herein may also be referred to as providing a forward cone angle to spacer 114, due to the fact that upon rotation of hub 110, the spacer describes a cone having its apex along the axis of rotation of the hub and its base in front or upwind of the rotor. The angle by which alignment axis A departs from plane N define the forward cone angle c of spacer 114. When aligned at a forward cone angle by a proper amount, a pitching moment of combination blade 108 at the base of spacer 114 is reduced or eliminated due to aft axial alignment of blade 116. Similarly, aft axial alignment of blade 116 is depicted by aft cone angle c', which is the acute angle by which A', the alignment axis of blade 116, departs from a plane N', a plane that is parallel to plane N. More preferably, forward cone angle c is greater than pitch angle p, which is the angle, if any, between P, the conventional pitch axis of the rotor and plane N. Desirably, the forward cone angle c of the present invention is at least 1 degree, preferably at least 7 degrees, more preferably at least 12 degrees, desirably at least 15 degrees, highly desirably at least 16 degrees, and most desirably at least 18 degrees. Further desirably, the forward cone angle c of the present invention is at most 45 degrees, preferably at most 40 degrees, more preferably at most 38 degrees, and highly desirably no more than 35 degrees. Desirable ranges for aft cone angle c' are at least 1 degree, more desirably more desirably at least 3 degrees, highly desirably at least 5 degrees, and most desirably at least 6 degrees; and a maximum of 10 degrees, more desirably a maximum of_9 degrees, and most desirably a maximum of 8 degrees. The skilled artisan will appreciate that the total length of blade 108, of root 114, and blade segment 116 as well as the height of the tower and the angle by which the wind turbine's rotational axis S is tilted up from horizontal will affect the angles c and c' employed, in as much as adequate clearance between blade tip and tower must be maintained. Highly desirably, the conventional pitch angle p of the present invention is between 0 degrees and 10 degrees, preferably from 2 degrees to 9 degrees and most preferably from 3 degrees to 7 degrees.

[0039] The respective lengths of spacer 114 (g) and blade 116 (g'), are selected so as to produce a desirable reduction of stress at the hub and of pitching moment experienced by the drive components. Moreover, during operation, because blade 116 is inclined with respect to normal plane N, a component of angular momentum (or centrifugal force) partially offsets wind forces acting to bend the blade rearward. Thus, suitable blades may be made thinner and lighter than conventional, radially aligned wind turbine blades and rearward thrust loads on hub bearings are reduced, especially under high wind conditions. Desirably, the spacer length, g, is a minimum of at least 5 percent of g', the length of blade 116, more preferably 10 percent, and most preferably 20 percent. Further desirably, the spacer maximum length is 50 percent of g', more preferably 45 percent, and most preferably 40 percent. In an even further desirable embodiment, the pitch angle, fore and aft cone angles, and respective lengths of spacer 114 and blade 116 are selected such that the pitch axis P intersects the alignment l axis A' of blade 116 at a point that produces minimal rotational moment, preferably at or near, that is, no more than 5 percent of blade length, g', from the center of mass of combination blade 108. Highly desirably, this point of intersection is from 25 to 50 percent of g' from the base of blade 116. Suitable blade lengths for use herein are from 20 m to 200 m, preferably from 30 m to 100 m. One specific application may employ a rotor diameter of about 110 m, and have a total swept area of 10,000 m^2 or more.

[0040] Due to forward cone angle c and aft cone angle c', the combination blades according to the invention possess improved aerodynamic properties due to the absence of any surface that might cause flat plate vortex generation and flutter under certain wind conditions. Also, the sudden arrival of an advancing storm generated wind gust or wall of hail from a storm does not impact the entire blade length simultaneously, possibly causing structural failure of the blade or rotor. An additional and unexpected benefit that is believed to result from the present design is greater visibility to birds. Because the outer portion of the spinning rotor is raked or inclined with the wind direction, soaring birds are likely to encounter a smaller portion of the blade sweep before becoming visually aware of the rotating blade. That is, downward looking birds, flying higher than the central portion of the present rotor design, will see the leading portions of the rotor in close proximity to themselves prior to entering the blade swept area at their flight level and experience an outward air flow from the aft swept blade, thereby improving their chances of avoiding the rotating blades.

[0041] In preferred embodiments of the present invention, spacers 114 are highly rigid with respect to both torsional and bending forces, desirably having an elastic limit that is at least three times, preferably at least four times, the maximum stress expected under operational conditions (design limit). Suitable materials of construction include glass fiber, carbon fiber, polyaramide fiber, or other high strength fiber or fabric reinforced resins and laminates comprising the same, as well as metals, especially aluminum, titanium or steel alloy castings or forgings. Because the latter materials are easier to fabricate than laminates or fiber reinforced resinous materials, their use for constructing the present spacers is preferred. The combination blades of the present invention have the advantage in that worn or damaged blades 116 may simply be replaced at reduced cost and inconvenience than is the case with the use of larger single piece blades. Construction, transportation and field mounting are also simplified due to reduced size and weight of the portion of the blade that needs to be replaced. The use of high strength metals as the materials of construction also allows the diameter or thickness of the spacer to be substantially reduced, or at least the longitudinally outer most portions thereof to be tapered, thereby reducing overall weight of the rotor and providing less aerodynamic drag. Although the cross-sectional shape of spacers 114 is unlimited and specifically may include an airfoil shape, for simplicity of construction and ease of assembly, spacer 114 desirably has a cross-sectional shape that is incapable of generation of substantial amounts of wind generated torque or power. That is, the cross-sectional shape of spacer 114 is desirably circular, oval, tear-drop or ellipsoidal shaped. Furthermore, said diameter or cross-sectional area, at least at or near the outer terminal portion thereof, is desirably smaller than the diameter or cross-sectional area of the innermost terminal portion of blade 116, not counting any mounting or fastening apparatus. One particular advantage of a spacer having an oval cross-sectional shape is that it can be readily fabricated from sheet steel or aluminum, welded along a single longitudinal seam, and shaped into circular cross-sections at the termini for convenient attachment to a conventional hub and blade.

[0042] It will also be observed that configurations of the present invention wherein the spacer possesses the foregoing shape and size produce a beneficial decrease in parasitic drag in the inner rotor area along with improved aerodynamic performance of the blade due to coupling of the thrust generating outer regions of the blade with an inner "donut" hole of relatively undisturbed air flow over the spacer. This results in movement of the center of pressure radially outward along the blade thereby maximizing torque and power generation. Highly desirably, spacer 114 is tapered, that is, it has a generally gradually decreasing diameter or cross-sectional major and minor axis measurements over a majority of the distance from the inner to the outer ends thereof (not counting any larger sized distal terminus and corresponding adjoining radii). Further highly desirably, spacer 114 is circular in cross-sectional shape over a majority of it's length. Because spacers according to the present invention may be designed purely for strength and not airfoil shaped, cheaper materials of construction, such as steel or aluminum, may be employed for their manufacture. Suitable aluminum alloys for use especially include high strength alloys such as 6000 or 7000 series alloys (International Alloy Designation System), and scandium containing alloys. Combination blades are attainable having larger effective blade lengths, the components of which are more durable and easily transported than single piece units, with little compromise of performance and even improved performance properties.

[0043] Referring again to FIG. 5, blade combination 108 may include a curved or bent region 112 in spacer 114, leading to aft acute angle of attachment for blade 116. The shape and size of distal terminus 202 is selected based on various criteria including the presence of attachment means for assembly of blades 116, aerodynamic concerns, or the presence of pitch control for blade 116 at the distal terminus. The skilled artisan will also appreciate that blade 116 may also include a curve or bend, if desired, and the resulting blade combination may include both curved spacer 114 and curved blade 116 without departing from the scope of the present invention.

[0044] As previously mentioned, in a highly preferred embodiment of the invention the pitch controllers are located in the distal terminus of the spacer. In as much as only the outer or working blade section is to be rotated by the pitch controller and the pitch axis and blade axis are more closely aligned, smaller and lighter pitch control mechanisms may be employed and a wider range of pitch control and faster pitch response times are attainable. In addition, if a pitch control mechanism is present in the distal terminus of spacer 114, it should be oriented such that the pitch control axis diverges with respect to the alignment axis A of the spacer and conforms rather with the alignment axis A' of the blade. With regard to construction and operation of pitch control mechanisms, regardless of location herein, any suitable design may be employed, including electromechanical or hydraulically actuated mechanisms as well as associated blade bearings including roller bearings or hydrostatic plain bearings. Examples of suitable pitch control mechanisms and systems for use herein include those disclosed in US-B's 8,430,632, 8,172,531, 8,096,762, 8,070,446 and 7,750,493.

[0045] Configurations of the present invention can be applied to an existing wind turbine by replacing conventional blades with the spacer and blade combinations of the present invention without the need for expensive upgrades of pitch drive hardware. Furthermore, use of spacers having reduced cross-sectional diameter, at least in the outer regions thereof according to the present invention results in improved aerodynamic performance of the resulting rotor design as well as increased blade longevity due to reduction in harmful pulsation and vibration generation under operating conditions or high wind conditions. Additional benefits include reduction in acoustic vibrations (noise) as well as the ability to operate safely at higher wind velocities thereby allowing power generation over wider ranges of wind conditions. Highly desirably, the foregoing benefits are obtained in designs of the present invention wherein conventional pitch axis P intersects the alignment axis of outer blade section 116 at a point that is between 25 and 50 percent of the length of outer blade section 116 from the base thereof.

[0046] It is to be understood that in addition to any forward and aft alignment, or cone angles, inclination of the spacer and/or blade with respect to the direction of rotor rotation, that is within a plane that is normal to the axis of rotation of the rotor, is also permitted. That is, the axes S and A or the axes S, A and A' may or may not be coplaner. Desirably, the distal terminus of the blade spacer is adapted such that the alignment axis of the outboard section or blade is disposed at an acute receding angle with respect to the direction of rotation of the rotor about its rotational axis. Referring to FIG. 6, in this embodiment of the invention, spacer 114 of blade 108 is attached to hub 110 such that the spacer alignment axis A, is aligned with the hub in a leading angle, f, with respect to radial line R, a line intersecting S and located in a plane that is normal to S. Accordingly, alignment axis A is disposed either axially (not depicted) or in a forward inclination with respect to the direction of rotation. The distal terminus of spacer 114 is adapted such that the alignment axis A' of blade 116 is oriented backward with respect to the direction of rotation D of the wind turbine thereby defining an angle f' with respect to radial line R. In such design, reduced stress at the blade base and improved stability of the rotor is achieved.

[0047] Desirably, the angles of forward inclination f, as above defined, may range between 0 degrees and 10 degrees, preferably from 0 degrees to 8 degrees, more preferably from 0 to 7 degrees, and highly desirably from 0 to 5 degrees. Desirable ranges for backward orientation f' are from 1 to 12 degrees, more desirably from 2 to 10 degrees, and most desirably from 2 to 8 degrees. In a most preferred embodiment, a plane containing radial line R and rotational axis S (not depicted in FIG.6) intersects alignment axis A' at or near the center of mass of combination blade 108. By near is meant the intersection point is within 5 percent of total blade length from said center of mass.

[0048] Blade 116 comprises the working airfoil of combination blade 108. In FIG.7 one suitable airfoil shape is depicted for a sample cross-section of blade 116 showing the upper or low pressure surface and bottom or high pressure surface of the airfoil. Desirably, highly asymmetrical airfoil designs are avoided, especially an airfoil design having negative camber in the trailing half of the blade, due to the large amount of drag created during usage and large shift in center of lift under varying wind conditions. Depicted is a modestly asymmetrical airfoil design such as a NACA 4412, or a Grant X series airfoil shape, or Grant X-8 through Grant X-10, (c.f., Charles Hampson Grant, Model Airplane Design and Theory of Flight, Jay Publishing Corporation, New York, 1942, pg. 27). Characteristics include a chord length X, that is the distance between front and rear chord starting points, half chord point f, half chord length, X_f, point of maximum chord diameter d, and length at maximum chord diameter, X_d. The shape of the airfoil joining upper and lower surfaces at the front leading edge is a partial circle having radius r_N. Desirably, the ratio of r_N/d is from 1/5 to 1/20, most preferably from 1/6 to 1/10. Highly desirably in order to reduce the incidence of insect strikes and resulting buildup on the leading edge of the blade (which leads to reduced aerodynamic efficiency and increased drag of the blade) r_N is relatively small, ideally from 10 to 50 mm, more preferably from 12 to 30 mm. In one embodiment of the invention blade 116 has a substantially constant chord length and airfoil shape , a substantially straight taper, or a combination of such shapes over at least the inner most 85 percent of blade section length, preferably at least the inner most 90 percent of blade section length. Further desirably the leading edge of the blade section 116 substantially conforms to a straight line and the blade section is twisted such that the outer most leading edge thereof has a reduced angle of attack with respect to the effective wind direction.

[0049] In addition, desirable airfoil designs include those having a center of lift close to the structural center of the blade as well as close to the center of mass thereof, more desirably between X_d and X_f. By close, is meant that the center of lift under working conditions is desirably within 10 percent of total chord length from the position on the chord closest to the airfoil's cross-sectional center of mass. Further desirably, the blade is designed and constructed of materials selected to provide a center of mass that is forward of the structural or geometric center of the blade as well as forward of the midpoint of the chord as well as the midpoint of the median line. One method of insuring that the center of mass of the blade conforms to the foregoing requirement is to include materials of construction having greater density such as steel, brass or iron components in the forward portions of the blade or to use designs containing more massive construction components in the forward portions of the blade. Most generally, the blade includes a box beam or other structural member to carry loads the axis of which is centered along the structural axis of the blade or at least parallel thereto.

[0050] FIG. 8 shows a cross-section of a suitable laminated blade 116 for use according to the invention having internal structural components 130 forming a box beam and outer surface skin 131 forming the lower and upper surfaces of the blade, the laminated structure forming a single mass. Suitable materials of construction include, without limitation, glass fiber, carbon fiber, polyaramide fiber, or other high strength fiber or fabric reinforced thermosetting resins, especially epoxy resins. The method of construction is controlled such that the center of mass of the resulting structure is located at a point forward of the center point of the chord, without addition of metal rods or beams in the front interior portion of the blade. However, in a desirable embodiment of the invention, additional mass may be included in the forward half of blade 116 by the inclusion of a metal rod or shaft 132. Highly desirably, this metal rod is steel or brass and is located in an extreme forward portion of the blade, especially adjacent to the leading edge of blade 116, or within 10 percent of the total chord distance from the leading edge, most preferably within 5 percent of the total chord length from the leading edge of blade 116. Alternatively, multiple rods or shafts may be included in the blade design, and if extending longitudinally end to end within the blade, are desirably joined into a single structure, such as by welding or brazing adjoining ends, to increase blade rigidity. Desirably rod or shaft 132 is long enough or multiple rods are joined together to extend for at least the outer 40 percent, preferably 50 percent, and most preferably 70 percent of the length of blade 116. Due to the concentration of mass in the present blade design in the stated forward position with respect to the structural axis of the blade, centrifugal forces generated by the blade rotation serve to partially or fully offset wind generated bending forces experienced by the rotating blade, leading to reduced stress and improved longevity of the present blade design.

[0051] Referring to FIG. 9 there is depicted in partial front view a wind turbine rotor according to the invention having combination blades 108 which include blade 116 which may be slightly tapered over all or a portion thereof, and which terminates with a relatively highly tapered outer end, 220 having length g", starting at a point 223 on the leading edge of the blade. Highly desirably, the relatively highly tapered section 220 is only tapered on the leading edge of the blade. That is, the width or chord length of blade 116 decreases, preferably linearly, from front to back proceeding longitudinally outward over the remaining length g' of the blade with the trailing edge remaining substantially in line with the trailing edge of the remainder of the blade. The length of relatively highly tapered section 220, that is, g", is desirably from 5 to 12 percent of g', the length of blade 116, more desirably from 6 to 10 percent. In one desirable configuration, the width of tapered outer end 220 at its outer extremity is from 75 percent to 50 percent of its initial width. The presence of tapering on the outer extreme end of the blade is desirable due to formation of a discontinuity in the leading edge at point 223 which causes vortices to be shed outward, especially at high angles of attack, resulting in a reduction in blade pulsation, oscillation, or vibration generation and improved aerodynamic performance. Additionally, ice build-up is more readily shed from the blade by the presence of an angled leading edge after point 223.

[0052] The cross sectional size of spacer 114 near distal terminus 202 may be smaller than the cross-sectional size of blade 116 near it's base, causing a discontinuation 206 where the leading edge of blade 116 joins spacer 114. That is, when viewed in profile, the leading edge of the blade, or at least the innermost portion thereof, describes a line or curve that, if continued in the direction of the spacer, does not intersect the spacer's forward edge. This desirably acts as a vortex generator, leading to improved aerodynamic response of the combination blade as changing wind conditions or gust induced air-stream separation is more likely to initiate at the base of blade 116 rather than further outward and is less likely to induce vibration and flutter in the blade combination. All outside and inside corners where blade section 116 joins spacer 114 may be chamfered, rounded, beveled, filleted, or fitted with a fairing or fairings without losing the foregoing advantageous property of the invention. Desirably, spacer 114 is tapered and hollow. The skilled artisan will appreciate that the portion of blade 116 identified as 206 may also be a separable adapter, union or connector which in combination with spacer 114 and blade 116 imparts aft cone angle to the spacer and blade combination. That is, the invention also comprises a combination comprising a spacer, an adapter, and a blade, said spacer being substantially rigid and adapted for attachment by it's proximal terminus to the hub of the wind turbine and further adapted for attachment by means of it's distal terminus to the base of a wind turbine blade by means of said adapter such that the alignment axis of the blade is disposed at an aft acute angle relative to the alignment axis of the spacer. In this embodiment, the adapter is substantially rigid or highly rigid, formed from a similar material of construction as the spacer or blade, especially metal such as steel or aluminum alloy, and fitted with flanges, studs, clasps or other attachment means for joining together the spacer and blade into a unitary structure. In this embodiment, adapter 206 need not be smaller in cross-sectional size than the cross-sectional size of blade 116 near it's base, and may in fact correspond in shape and function to the bend 112c identified in FIG. 3c.

[0053] Also depicted in FIG. 9 is a protective surface cover or coating 140 applied or bonded to some or all of the leading edge of blade 116, for example sheet metal such as copper, brass, tin, stainless steel, or steel. Desirably, the cover or coating is applied to at least the outermost 10 to 20, more preferably 10 to 50 percent of the blade length. The coating may also comprise a durable, non-metallic hard surface such as ceramic or other impact resistant material. The purpose of the protective surface cover or coating is to protect the blade leading edge from impact with hail or other hard objects as well as to increase the mass located forward of the structural center of the blade. Suitably, the leading edge surface for a distance from 1 to 10 percent of total distance to the trailing edge above and below the blade center line is covered by the protective surface coating. As an aid in the dissipation of electrical charge and prevention of lightning strikes, the leading edge surface covering, if conductive, may also be grounded, through connection to a suitable grounding point (not illustrated). The skilled artisan will appreciate that the spacer of the invention must itself be conductive and grounded or include therein a conductor connected to ground for completion of the grounding circuit with surface cover 140 in this embodiment of the invention. The point identified as 224 marks an inflection point on the high pressure surface of the blade where an optional sloping end cap begins.

[0054] In FIG. 10 there is depicted a blade comprising multiple sections 116a, 116b and 116c, each comprising a protective coating 140a, 140b and 140c respectively, on the surface of the leading edge of one or more blade segments. The leading edge of each segment describes substantially a straight line however, each succeeding section proceeding outward toward the blade tip progressively narrows, due, at least partially, to slight angling of the leading edge. The difference in angle of the leading edge between two representative segments is indicated by q, the amount by which two adjacent blade segments differ in outer blade width. The skilled artisan will appreciate that the amount by which adjacent blade segments differ in width may or may not remain constant and the numbers of such segments per blade is not limited, but is preferably a number from 3 to 10. Each segment length likewise is variable and the portion of the blade in which such segmented construction occurs is desirably at least the outer most length of the blade, most preferably at least the outermost 25 percent, more preferably the outermost 50 percent, and most preferably the outermost 75 percent of blade length. Because each segment's leading edge is substantially linear, sheet metal may be readily shaped to conform to the leading edge, with the entire blade thereby approximating a curved leading edge over the course of its length. Preferred metals for use in this embodiment of the invention include aluminum, steel, galvanized steel, brass or titanium. A desirable benefit of employing such a segmented, leading edge comprising a protective coating or cladding, besides imparting impact and abrasion resistance to the blade's leading edge, is that the multiple discontinuations in leading edge angle between segments provide desirable vortex generation along the blade length, thereby improving blade aerodynamic properties.

[0055] Referring to FIG. 11, in some embodiments of the invention, the distal portion of blade 116, regardless of the presence of tapering along the blade length, terminates in a sloped end piece or cap 222 starting on the high pressure side of the blade at previously identified point 224 on the blade surface and in a plane perpendicular to the structural axis and terminating on the low pressure side of the blade. The angle at which the sloped end piece 222 is inclined with respect to the structural axis is indicated by angle t. Desirably, t is an angle from 30 to 60 degrees, more preferably from 40 to 50 degrees, and most desirably 43-47 degrees. The purpose of slopping the end of blade 116 by means of end cap 222 is to allow gradual recombination of high and low pressure air streams and also to cause the ensuing vortex to be directed outside the radius of the spinning rotor. This greatly reduces flutter, vibration and noise generation by the spinning turbine rotor. Most desirably, the point 224 is located at approximately 85 to 99 percent of the distance of g' starting at the base of blade 116, most desirably from 87 to 98 percent of the distance g'. The skilled artisan will appreciate that blade end 222 need not form a flat surface as depicted, but may also be a rounded or curved surface, without departing from the scope of the invention.

[0056] Referring to FIGs. 12 (end view) and 13 (frontal view), in additional embodiments of the invention, blade end 222 comprises a fin 225 which, with respect to its point of attachment to blade 116, projects both outward (above) and behind the trailing portion of blade 116 on the low pressure side thereof and terminates in an apex 226 located outward and behind the trailing edge of blade segment 116. Desirably, fin 225 extends above the upper surface of blade 116 for a distance that is from 10 to 50 percent of the blade thickness measured at point 224, and extends behind the trailing edge of blade 116 for a distance that is from 2 to 10 percent of the blade chord length measured at point 224. In operation, fin 225 causes the vortex formed upon recombination of high and low pressure air masses on opposite sides of blade segment 116 to be directed further outside and behind the blade than is obtainable with only a sloped blade end or cap, thereby further reducing pulsation, oscillation, or vibration generation by the rotor blade. Highly desirably, fin 225 is also conductive and is grounded by means of a conductor 227 which is connected through the blade to a suitable grounding source and connected to fin 225 by an electrically conductive connector 229. Due to rotation of the turbine rotor, conductor 227 may ultimately require connection to ground via a commutator or other rotating electrical connection (not depicted) within the turbine hub in order to form a suitable connection to fin 225. An additional advantage of inclusion of electrical conductor 227 in the location depicted, forward of the structural axis of the blade, is to provide additional mass in the forward portion of the blade as previously discussed. Ideally, conductor 227 is securely attached within the interior of blade 116 within 20 percent, preferably within 15 percent of total chord length from the leading edge of the blade. Alternatively, the entire blade segment 116 or a portion thereof may be formed of conductive materials such as aluminum or steel and suitably attached to conductive fin 225 and a grounding source to thereby effectively ground fin 225. Suitable materials of construction of conductive fin 225 include metal, especially steel, brass or aluminum, as well as electrical conductive laminated materials such as the previously mentioned metal mesh reinforced laminated materials. The thickness of fin 225 may vary within wide tolerances, but generally is from about 2 to 20 mm in maximum thickness. Although depicted as a flat plate with squared off edges, the skilled artisan will appreciate that fin 225 may be rounded or curved on its edges, sides and surfaces as well as embossed, engraved, grooved, or otherwise shaped, if desired. In addition, the ends of the blade may include holes to allow inspection of the blade interior, drainage of water or other accumulated liquids, or internal pressure relief as well as projections for purposes of lightening reception and conduction, or other use.

[0057] The purpose of providing a grounded fin is to enhance dissipation of static electricity from the blade surface through a corona discharge from the tips of the blade, thereby reducing the incidence of damage to the blades of the invention due to lightning strikes. When employed in combination with a metallic covering for impact protection of the leading edge of the blade which also serves as at least a portion of the electrical grounding circuitry, an additional desirable benefit to the present design is achieved, since an internal conductor or wiring is not required to be included within the blade itself or a smaller sized grounding conductor may be employed. It will again be appreciated by the skilled artisan, that the spacer of the invention must itself be conductive and grounded or include therein a conductor connected to ground for completion of the grounding circuit with fin 225 in this embodiment of the invention. Preferably, the spacer is electrically conductive and serves partially or wholly as a lightening strike ground conductor or a static discharge ground conductor.

[0058] The skilled artisan will appreciate that the working blade section of the present wind turbine blades, or at least the outermost regions thereof, may include a lengthwise twist to better match the airfoil to the apparent wind angle. This ideally allows the outermost regions of the blade to maintain thrust under reduced wind speeds or varying wind conditions thereby avoiding vibration or flutter inducing conditions. All of the previously disclosed modifications to blade design including longitudinal and cross-sectional tapering and fin placement also contribute to the foregoing improved aerodynamic properties. In addition, the skilled artisan will appreciate that when incorporated into a rotor, additional linkages, such as cables, spars or tensioning stays may be incorporated to join the forward most regions of spacers and blades disclosed herein thereby more evenly distributing centrifugal forces within the rotor.

[0059] Example 1

[0060] A wind turbine having a rotor equipped with three blades is provided having a design rating of 8 Mw. The blades are comprised of spacers of circular cross-section 24 m long, with proximal diameter 3.7 m, distal diameter 2.0 m, disposed at a 20 degree forward alignment angle (forward cone angle). The working blades are 56 m long and disposed at 7 degree aft alignment angle (aft cone angle). The axis of rotation is tilted up approximately 5 degrees. Blade tip clearance in front of the base is approximately 7 m, and blade loading is 122 kg/m^2.

[0061] Although described in several embodiments, preferred, more preferred, most preferred, desired, more desired, most desired embodiments, and other alternative language, it is intended that various combinations of the presently described embodiments and portions thereof may all be employed in a single design without departing from the scope of the present invention; that such combinations are intended to be fully enabled by the present description; and that minor variations in design, form or application of the presently disclosed embodiments are included in the present inventive concept. In particular, the following specifically disclosed embodiments of the invention are provided as enablement for the attached claims.

Embodiments

1. A blade spacer for use on a forward running wind turbine, said spacer being substantially rigid and comprising a proximal terminus adapted for attachment to a wind turbine hub such that the alignment axis of the spacer is disposed at an acute forward angle (cone angle) relative to a plane that is normal to the axis of rotation of the hub and a distal terminus adapted for attachment to the base of a wind turbine blade such that the alignment axis of the blade is disposed at an aft acute angle relative to a plane that is normal to the axis of rotation of the hub.

2. A blade spacer according to embodiment 1 wherein said forward cone angle is from 1 to 45 degrees.

3. A blade spacer according to embodiment 1 or 2 wherein said aft acute angle is from 1 to 10 degrees.

4. A blade spacer according to any of embodiments 1-3 additionally comprising a pitch control mechanism in the distal terminus thereof for adjusting the angle of attack of the blade.

5. A blade spacer according to any one of embodiments 1-4 having a cross-sectional shape that is incapable of generation of substantial amounts of wind generated torque.

6. A blade spacer according to any one of embodiments 1-5 that is tapered from larger to smaller cross-sectional shape over a major portion of the distance from proximal terminus to distal terminus.

7. A combination comprising a blade spacer and a blade for use in a forward facing wind turbine, wherein the blade spacer corresponds to any one of embodiments 1-6.

8. A combination according to embodiment 7 wherein the length of the spacer is from 5 to 50 percent of the length of the blade.

9. A combination according to embodiment 7 wherein the length of the spacer is from 10 to 50 percent of the length of the blade.

10. A combination according to embodiment 7 wherein some or all of the blade leading edge is covered with a protective surface cover or coating.

11. A combination according to embodiment 10 wherein the protective surface cover is sheet metal.

12. A combination according to embodiment 11 wherein the protective surface is grounded by means of an electrically conductive spacer or a conductor passing within the spacer.

13. A combination according to embodiment 7 wherein the distal portion of the blade is tapered only on the leading edge.

14. A combination according to embodiment 7 wherein the distal portion of the blade terminates in a sloped end starting on the high pressure side of the blade and terminating on the low pressure side of the blade.

15. A combination according to embodiment 13 wherein the sloped end comprises a fin which, with respect to its point of attachment to the blade, projects both outward and behind the trailing portion of the blade on the low pressure side thereof and terminates in an apex located outward and behind the trailing edge of blade section.

16. A combination according to embodiment 14 wherein the fin is conductive and is grounded.

17. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to embodiment 7.

18. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to embodiment 8.

19. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to embodiment 12.

20. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to embodiment 13.

21. A blade spacer according to embodiment 1 wherein said forward cone angle is from 12 to 40 degrees.

22. A blade spacer according to embodiment 1 wherein said forward cone angle is from 16 to 38 degrees.

23. A blade spacer according to embodiment 3, 21 or 22 wherein said aft acute angle is from 3 to 9 degrees.

24. A blade spacer according to embodiment 3, 21 or 22 wherein said aft acute angle is from 6 to 8 degrees.

25. A blade spacer according to embodiment 1 wherein the forward cone angle is greater than the pitch angle of the combination blade.

26. A blade spacer according to any one of embodiments 1-6 wherein aft orientation of the blade at the distal terminus of the spacer arises due to a bend in the spacer.

27. A blade spacer according to embodiment 4 wherein the pitch control mechanism is oriented such that the pitch control axis diverges with respect to the alignment axis of the spacer.

28. A blade spacer according to any of embodiment 1-27 that is tapered over a majority of the distance from proximal terminus to distal terminus.

29. A combination comprising a blade spacer and a blade for use in a forward facing wind turbine, wherein the blade spacer corresponds to any of embodiments 1-28.

30. A combination according to any of embodiments 1-29 wherein the length of the spacer is from 5 to 50 percent of the length of the blade.

31. A combination according to embodiment 30 wherein the length of the spacer is from 20 to 50 percent of the length of the blade.

32. A combination according to any of embodiments 1-31 wherein the blade cross sectional shape and chord length are substantially constant or the blade is straight tapered over at least 85 percent of the blade length and the leading edge thereof substantially conforms to a straight line.

33. A combination according to embodiment 32 wherein some or all of the blade leading edge is covered with a protective surface cover or coating.

34. A combination according to embodiment 33 wherein the protective surface cover is sheet metal.

35. A combination according to embodiment 34 wherein the protective surface is grounded by means of an electrically conductive spacer or a conductor passing within the spacer.

36. A combination according to any of embodiments 1-31 wherein the distal portion of the blade's cross-sectional chord length is tapered beginning from the leading edge.

37. A combination according to embodiments 32-36 wherein the distal portion of the blade terminates in a sloped end starting on the high pressure side of the blade and terminating on the low pressure side of the blade.

38. A combination according to embodiment 37 wherein the sloped end comprises a fin which, with respect to its point of attachment to the blade, projects both outward and behind the trailing portion of the blade on the low pressure side thereof and terminates in an apex located outward and behind the trailing edge of blade section.

39. A combination according to embodiment 38 wherein the fin is conductive and is grounded.

40. A combination according to embodiment 39 wherein the fin is grounded by means of an electrically conductive spacer or a conductor passing within the spacer.

41. A rotor for a forward running wind turbine, said rotor comprising a hub and at least one blade and spacer combination according to any of embodiments 29-40.

42. A wind turbine comprising a rotor according to embodiment 41.

CLAIMS:

1. A blade spacer for use on a forward running wind turbine, said spacer being substantially rigid and comprising a proximal terminus adapted for attachment to a wind turbine hub such that the alignment axis of the spacer is disposed at an acute forward angle (cone angle) relative to a plane that is normal to the axis of rotation of the hub and a distal terminus adapted for attachment to the base of a wind turbine blade such that the alignment axis of the blade is disposed at an aft acute angle relative to a plane that is normal to the axis of rotation of the hub.

2. A blade spacer according to claim 1 wherein said forward cone angle is from 1 to 45 degrees.

3. A blade spacer according to claim 2 wherein said aft acute angle is from 1 to 10 degrees.

4. A blade spacer according to claim 1 additionally comprising a pitch control mechanism in the distal terminus thereof for adjusting the angle of attack of the blade.

5. A blade spacer according to claims 1 having a cross-sectional shape that is incapable of generation of substantial amounts of wind generated torque.

6. A blade spacer according to claim 1 that is circular in cross-sectional shape over a majority of it's length and is tapered in the direction from proximal terminus to distal terminus.

7. A combination comprising a blade spacer and a blade for use in a forward facing wind turbine, wherein the blade spacer corresponds to claim 1.

8. A combination comprising a blade spacer and a blade for use in a forward facing wind turbine, wherein the blade spacer corresponds to claim 4.

9. A combination according to claim 7 wherein the length of the spacer is from 5 to 50 percent of the length of the blade.

10. A combination according to claim 7 wherein some or all of the blade leading edge is covered with a protective surface cover or coating.

11. A combination according to claim 10 wherein the protective surface cover is sheet metal.

12. A combination according to claim 11 wherein the protective surface is grounded by means of an electrically conductive spacer or a conductor passing within the spacer.

13. A combination according to claim 7 wherein the distal portion of the blade is tapered only on the leading edge.

14. A combination according to claim 7 wherein the distal portion of the blade terminates in a sloped end starting on the high pressure side of the blade and terminating on the low pressure side of the blade.

15. A combination according to claim 13 wherein the sloped end comprises a fin which, with respect to its point of attachment to the blade, projects both outward and behind the trailing portion of the

blade on the low pressure side thereof and terminates in an apex located outward and behind the trailing edge of blade section.

16. A combination according to claim 7 additionally comprising an adapter to join the spacer and blade wherein said adapter imparts an aft cone angle between the alignment axis of the blade and the alignment axis of the spacer.

17. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to claim 7.

18. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to claim 8.

19. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to claim 12.

20. A forward running wind turbine comprising a rotor, said rotor comprising a hub and at least one blade and spacer combination according to claim 13.

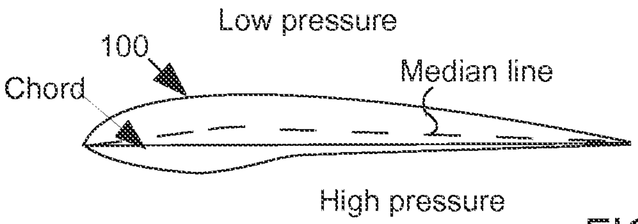


FIG 1

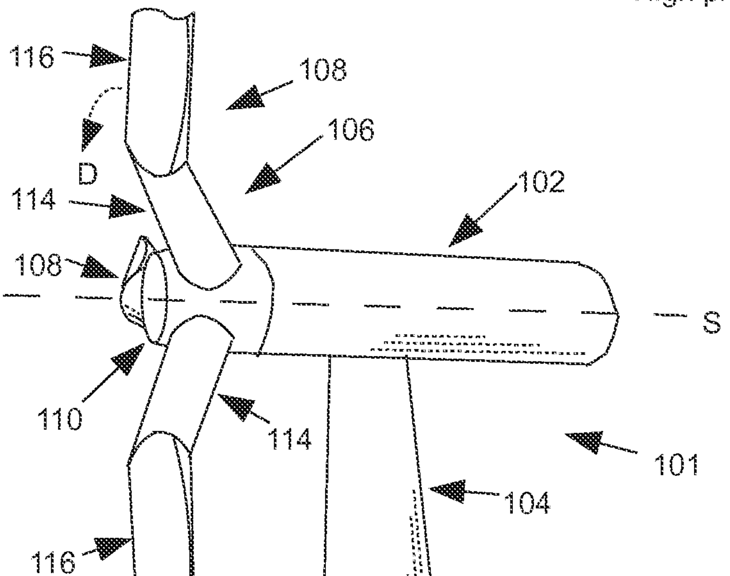


FIG 2

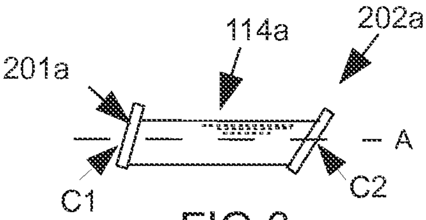


FIG 3a

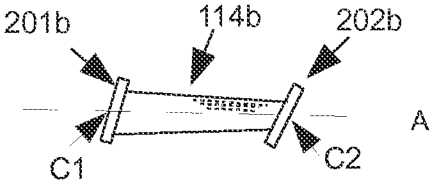


FIG 3b

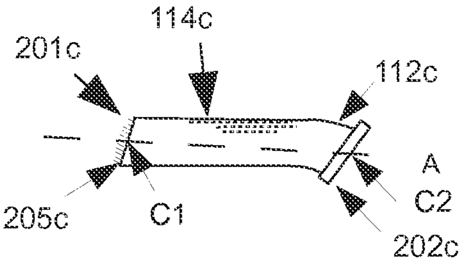


FIG 3c

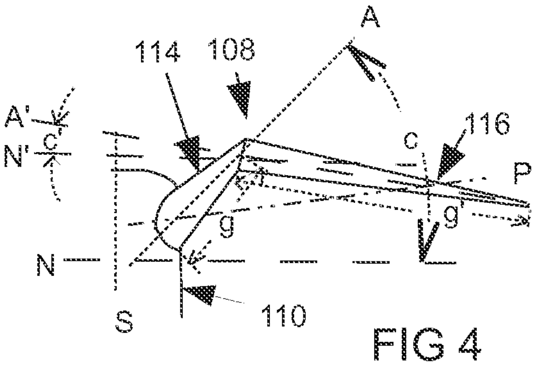


FIG 4

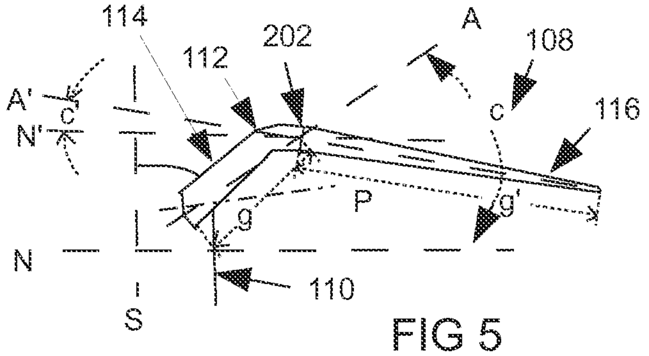


FIG 5

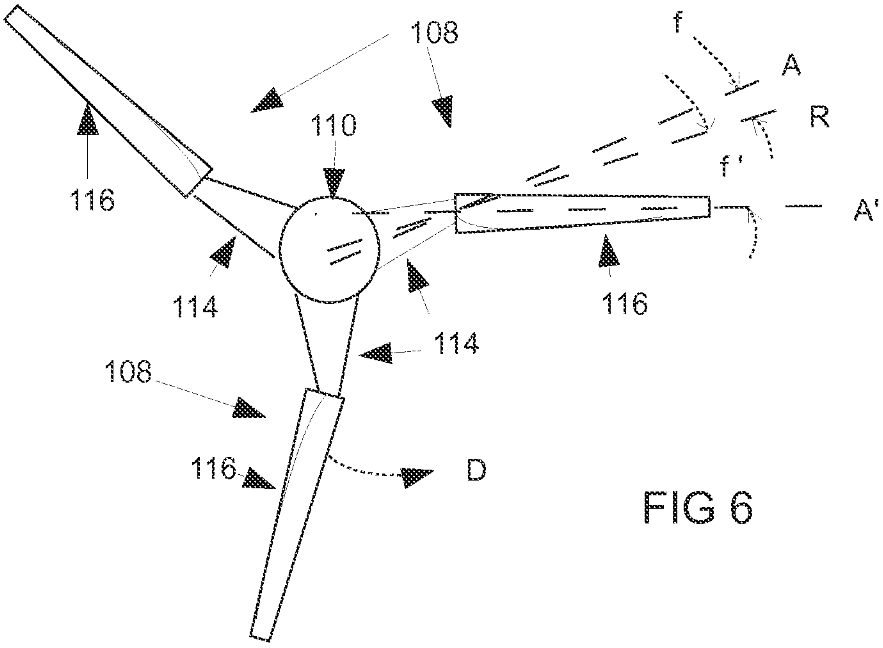


FIG 6

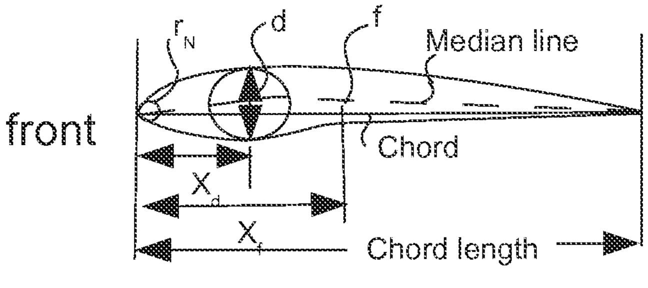
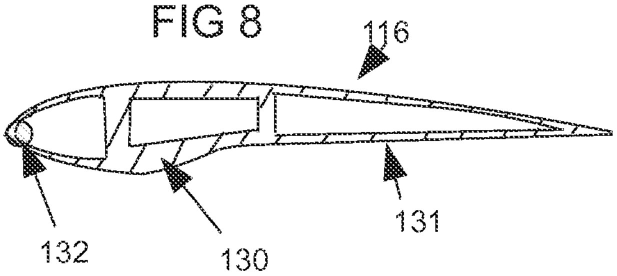


FIG 7

FIG 8



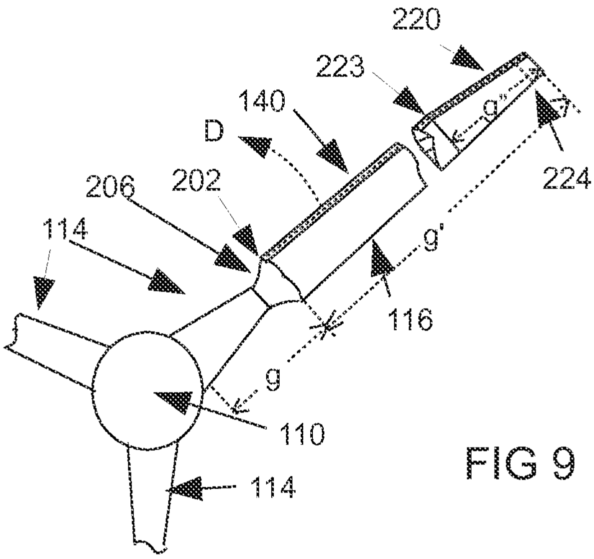


FIG 9

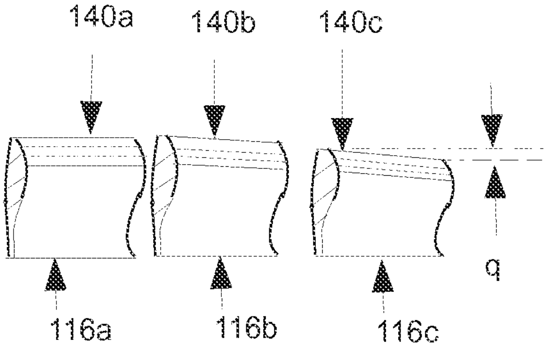


FIG 10

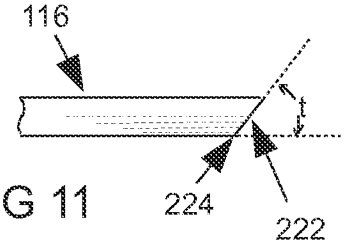


FIG 11

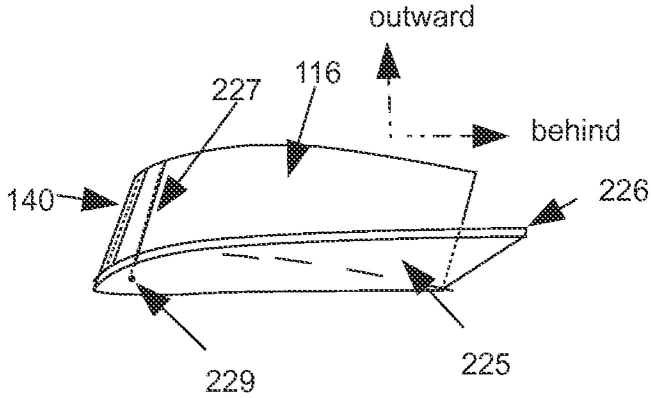


FIG 12

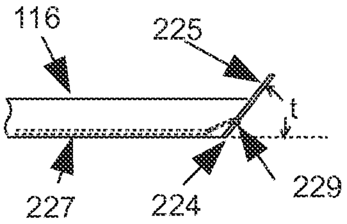


FIG 13

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US15/44131

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F01D 5/30; F03D 11/04 (2015.01)
CPC - F01D 5/30; F03D 11/04
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) Classification(s): F01D 5/30; F03D 11/04 (2015.01)
CPC Classification(s): F01D 5/30; F03D 11/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data), ProQuest, Google, Google Scholar
Wind, turbine, generator, blade, cone angle, taper, ground, electrically conductive, spacer, adjust, flexible, degrees, sheet metal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2012/0257974 A1 (MOK P) 11 October 2012; figures 1, 4; paragraph [0018]	1-3, 5, 7, 9, 14, 16, 17 --- 10-12, 19
Y	US 2010/0272570 A1 (AROCENA DE LA RUA I) 28 October 2010; figure 7; paragraph [0015]	10-12, 19
A	US 2012/0257977 A1 (JENSEN LE) 11 October 2012; entire document	1-20
A	US 4,533,297 A (BASSETT, DA) 06 August 1985; entire document	1-20
A	US 6,974,307 B2 (ANTOUNE IL) 03 December 2005; entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 13 October 2015 (13.10.2015)	Date of mailing of the international search report 10 NOV 2015
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774