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Morphing Segmented Wind Turbine Concept

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A morphing segmented concept is proposed herein for future extreme-scale wind turbine systems. The morphing may be accomplished by using segmented blades connected by screw sockets and a tension cable system. At low wind and rotor speeds, the segmented blades are fully tensioned and set at high pitch to ensure start-up and maximum power at low speeds. At high rotor rpm, the cable tension can be designed such that centrifugal forces drive the blade segments outward so as to unwind/feather the rotor and prevent over-speed. This effectively acts like a passive pitch control for rotor speeds. Perhaps more importantly, the airfoils of the blade segments can be designed with a center of pressure downstream of the socket axis. This will cause an aerodynamic moment at high wind speeds which will serve to unwind the blade segments to prevent torque spikes and blade stall. For a given rotor diameter and torque, such stall prevention can permit operation at higher average lift coefficient with a reduced blade chord length which can reduce blade and overall system weight. In addition, the segmented blade concept can alleviate manufacturing and shipping constraints for extreme-scale systems. In the proposed concepts, the bending loads will be carried by the segmented rotor spar and not the blade skin. This will result in much larger downstream deflections of the blades at high wind speeds as compared to that of a conventional rigid single-piece turbine blade. Therefore, a downstream design would be needed to avoid potential strike of the blades with the tower. This will require a more aerodynamic tower to reduce wake interactions but a downstream system may eliminate yaw-control and substantially relax blade rigidity constraints, thus further reducing blade weight. However, this morphing concept faces several technical challenges including substantially increased susceptibility to flutter instability and dynamic stall which is expected to require active control systems.

I. Introduction

WIND energy is key to the nation's 2030 goals of increased energy independence and reduced environmental impact stemming from power generation (Lindenberg *et al.* 2008). It is projected to account for as much as 20% of U.S. power by 2030. This sustainable source will improve the nation's energy independence and allow a low environmental impact as compared to traditional fossil fuels in many ways. Firstly, it can reduce energy related emissions since the 20% wind penetration by 2030 is estimated by DOE to avoid 2,100 million metric tons of carbon into the atmosphere. Secondly, estimates by Jacobsen (2009) indicate that 300 GW of wind power primarily used for charging electric-battery vehicles would eliminate 15,000 emissions-related deaths per year by 2020. This would also eliminate 15 million barrels per day of imported oil in the United States, reducing the amount of imported energy and increasing our energy independence and security.

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Maintaining or lowering cost of energy while simultaneously ramping up total installed penetration may benefit from revolutionary advances in turbine concepts at extreme-scales (diameters of 120 meters and beyond) with improved efficiency. This increase in scale and efficiency has been evident in recent wind turbine design. The average wind turbine rated power has increased twenty-fold since 1985, with present systems averaging 2 MW. Economies of scale and higher winds aloft are driving systems to power levels of 5 MW and beyond with rotor diameters (D) nearing 120 m and greater. While larger systems are needed in the future, blade weight (currently proportional to $D^{2.35}$) has become a constraining design factor due to high gravity loads (Ashwill, 2009). This scaling is important since system costs scale at least linearly with system weight and since the rotor itself accounts for about 23% of the initial total system cost (Fingersh, 2006). In addition, noise (and visual) production is likely to be very significant for extreme-scale systems indicating that such systems are best suited for off-shore siting. Such siting may also reduce many existing environmental impacts but leads to complications in terms of installation and maintenance. These problems are compounded by upwind turbine configurations since such designs necessitate stiff blades to avoid rotor-blade tower strikes. Moreover, overly rigid rotor/tower systems lead to problematic high-frequency fatigue loads. As such, a concept based on lightweight deforming blades may help mitigate structural loads and generator torque spikes, thereby creating a new paradigm for energy systems. This adaptability can also reduce the generator component to further reduce system cost and complexity.

Adaptable blade geometry is not a new concept and in fact has been used on many successful (and unsuccessful) systems over the last fifty years. The Jacobs governor used pre-tensioned hub springs which reduced the pitch at high centrifugal forces due to the weight of the blades themselves to reduce the pitch of all three blades simultaneously (to ensure aerodynamic balance). The concept allows the blades to slide outward along a shaft and feather due to a spider connector. An example of a design that uses active coning (or unfurling) to bend the blades back in the direction of the wind is the Soft Rotor concept designed by Rasmussen *et al.* (1998). A downwind system was employed to avoid tower interactions associated with such coning, and this also allowed a free-yawing concept to eliminate the need for mechanical yaw control. A two-bladed 15-kW version of this design was field tested where the power and loads were controlled by active stall and coning. Comparison with a similar rigid blade system indicated that rotor loads were reduced by 25-50% during operation as well in a "parked" position and in extreme winds. In addition, it was found that aerodynamic efficiency for flexible and coned rotors was approximately equal to that of rigid rotors of the same disk area.

II. Concept and Advantages of a Morphing Segmented Turbine

To address the needs of future wind turbine design, this paper introduces a turbine blade concept that adapts its geometry to changing flow conditions. In particular, novel morphing segmented blades are proposed to be used to reduce system weight (and thus cost). Herein, it is proposed that conventional, relatively stiff, single-element wind turbine rotor blades (Fig. 1a) be replaced with blades that employ centrifugal and aerodynamic tailoring to change their effective pitch and shape (Fig. 1b) using segmentation (Fig. 1c). This concept is similar to previous designs which employed centrifugal or aerodynamic forces to control rotor loading, but it is novel in its use of geometry morphing and blade segmentation.

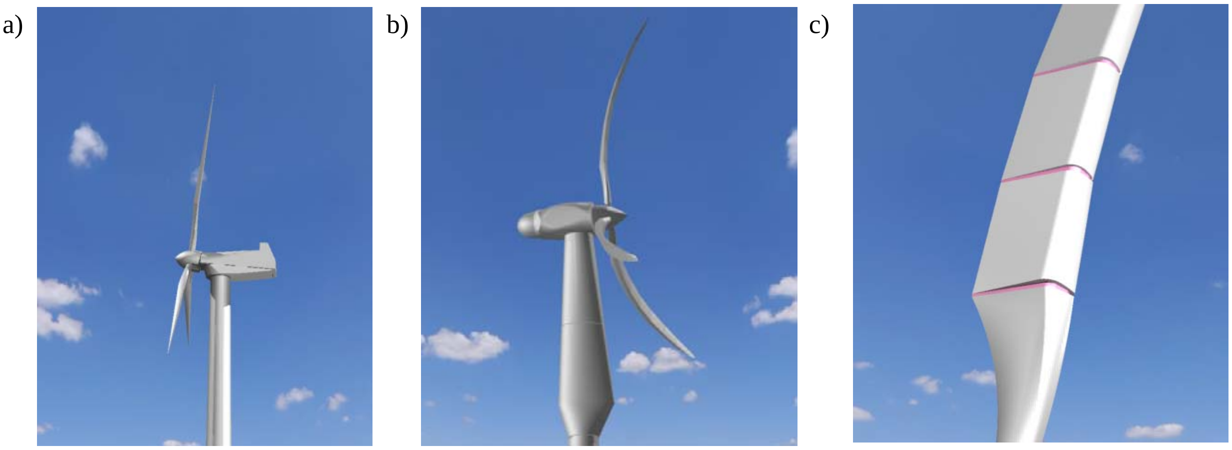

Figure 1. Concept of: a) conventional turbine, b) morphing turbine (with shroud around the mast and generator housing) and c) blade segments (joined with an elastomeric material).

A downstream configuration is needed because of the expected large downstream deflections. As such, the nacelle and the tower should be faired aerodynamically to reduced distortion see by the turbine blades. The blade segmentation aspect can be especially transformative with respect to manufacturing, transporting, and repairing such systems. This modularity, coupled with the reduced overall system weight can breakdown barriers inherent to increasing the scale of current turbine designs. To achieve this blade segmentation and adaptability requires a fundamentally new structural design. In particular, it is envisioned that the circular spars within the blade segments (near the quarter-chord line) can be socketed together in threaded joints. These joints will be designed to have nearly zero friction (e.g. housed in a hydraulic joint) and the segments are held together by a tension cable as shown in Fig. 2. The tension cable will run from the blade tip to the rotor hub where it can be attached by a spring and dash-pot damper system (dash-pots may also be placed at the joints). A hub cam can be used to provide eccentricity so that the cable tension remains constant despite changing gravitational loads as the blades move from the up to down positions.

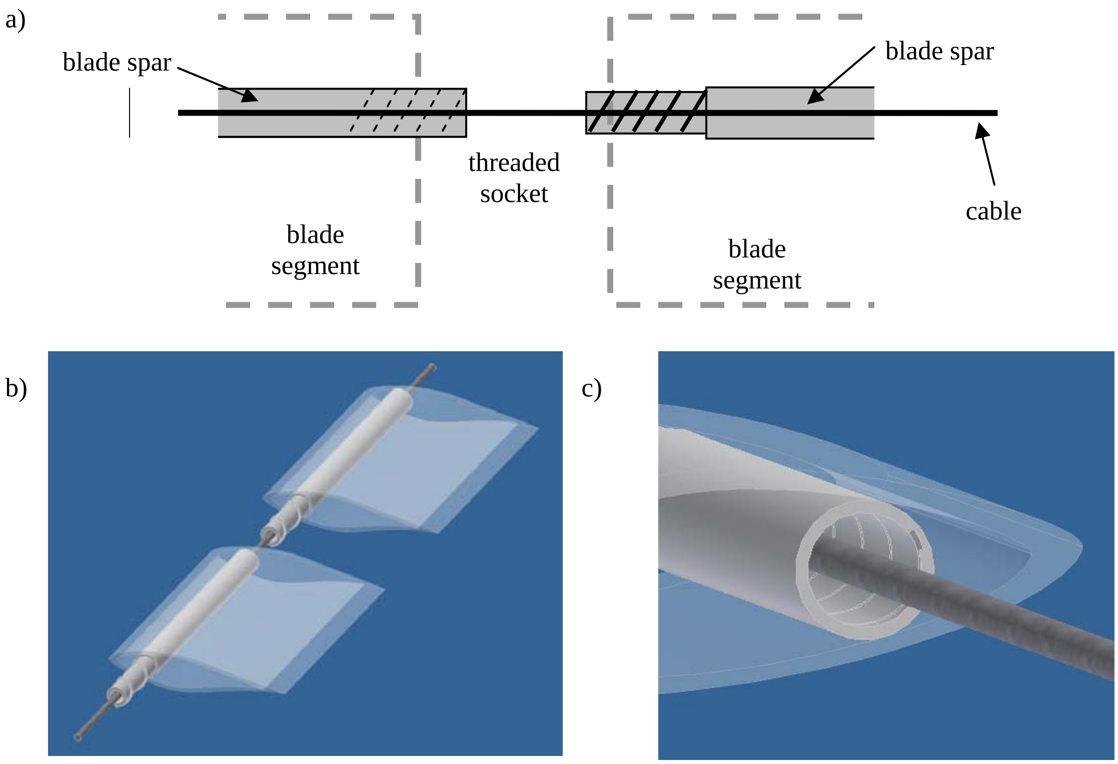

Figure 2. Concept of threaded socket between two blade segments showing exploded view (before joining): a) diagram view from above, b) illustrated perspective view, c) illustrated close-up of internally- threaded portion.

At wind speeds below the rated wind speed, this cable tension will be set so that the blades segments are “fully-threaded” (Fig. 3a). The fully-threaded position will be associated with the maximum geometric twist of the blade from the plane of rotation, to give a reasonable angle of attack for low winds. At wind speed increases beyond the rated speed, the rotor tip speed will also increase but a constant power is desired to match the generator capability. The tension can be set so that the increased rpm will result in centrifugal forces which will cause the segments to pull apart and thus unwind to reduce the effective angle of attack and maintain constant power (Fig. 3b). The blade segmentation will lead to small structural gaps but these can be covered with an elastomeric sheath (not shown in Fig. 3) to aerodynamically cover the gap extension resulting from any amount of unwinding. This feathering will tend the blade toward an optimum pitch to prevent stall and the associated unsteady torques. This control is similar to that used in a Jacob turbine whereby centrifugal forces change pitch (by overcoming spring tension) to avoid over-speed. Note that the Jacob’s concept ensured that all three blades changed pitch simultaneously. While the present concept does not ensure this same consistency mechanically, the addition of fine-scale pitch control (e.g. with fast-acting tabs) may be sufficient to keep aerodynamic balance for extreme-scale systems. The threading angle at each joint can be uniquely designed to achieve optimum twist changes over the most outboard (power producing) blade span at each wind-speed (which is associated with a unique quasi-steady turbine rpm). Segmenting allows much higher effective twist control than single-element concepts since small angles between segments can lead to large overall twist. This is desirable since the optimal pitch angle can vary by as much as 20 deg. above the rated wind speed (Wilson, 2009). This quasi-steady speed-tailored feathering can reduce the need for dynamic pitch control (which may help reduce overall system mass and thus cost) though full-span pitch control and system braking will still be needed to prevent over-speed above the set maximum blade rotation rate.

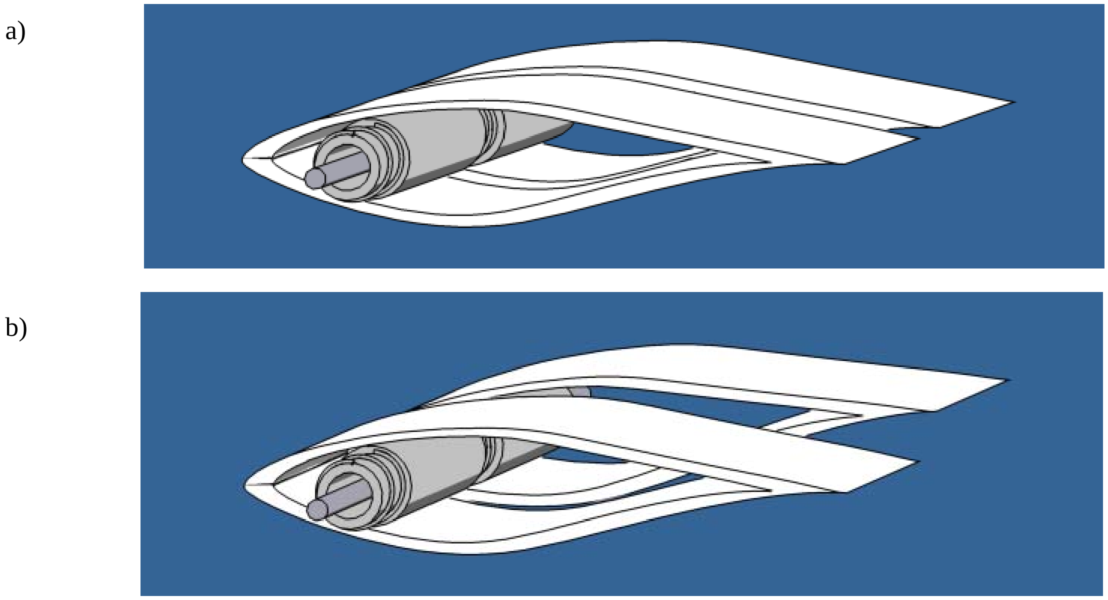

Figure 3. Concept of threaded socket between two blade segments showing: a) fully-wound condition for low speeds, and b) unwound condition for high speeds, where an outboard segment is faired in a relative sense.

While the above centrifugal-morphing can help at quasi-steady conditions, it can not accommodate high frequency wind speed gusts since the rotor rpm remains fairly constant (due to high rotational inertia). Such gusts are problematic as they caused temporarily increased aerodynamic angles of attack which can lead to unsteady torque spikes which can occur within a fraction of a revolution. Such spikes are undesirable in terms of both structural fatigue and power generator efficiency. Furthermore, these gusts may also lead to local stall conditions which may result in deleterious drag loads and unsteady buffeting. Since the socket joints will allow additional bending of the spar out of the rotation plane at high aerodynamic loads and since a downstream design has been employed, one option is to use the soft rotor concept which has been demonstrated previously to reduce torque loads (Rasmussen *et al.* 1998). However, it should be noted that this control based on “coning” can not fully alleviate the extra torques caused by wind gusts. Furthermore, the spar bending will be counteracted at high rotor rpm by centrifugal stiffening for moderate-scale systems (Loth, 1978) and will be complicated by gravitational loading for extreme-scale systems. Therefore, this coning effect only partially addresses torque spikes and may only be consistently effective at low rpm conditions.

A more robust technique may be to design the blades so they morph due to aerodynamic chord moments. In particular, the spar axis may be placed upstream of the aerodynamic center. This can be achieved with careful airfoil design (and/or the use of micro-tabs at the trailing edge). In this manner, a rapid increase in lift force will result in a moment about the spar which will unwind the blade. This will reduce the effective angle of attack thereby unloading the blade to prevent a torque increase. Similarly, a quick lull in wind speed (e.g. associated with passing though the wake resulting from the tower) can cause the blades to rewind to higher twist angles to help maintain torque, to a degree. Since this aerodynamic feedback can stabilize the blade torque, it may reduce unsteady structural and power generator loads. In addition, it may allow a more uniform effective angle of attack despite wind speed fluctuations which may permit operation at higher overall lift coefficients (since over-speed margin may be reduced and since the soft rotor concept may allow thinner blade thicknesses). This increase in lift coefficient can translate into reduced chord lengths and thus overall weight of the blades as compared to conventional turbines of the same power-level. In addition, the conventional hub-based mechanical pitch control may be only to fair the blades for full braking of the turbine. Furthermore, the downstream design may also reduced or eliminate yaw-control. These potential reductions in mechanical control and/or blade count may consequently reduce system weight, which is critical to economic viability and wide-spread adaption of extreme-scale systems.

III. Disadvantages of a Morphing Segmented Turbine

Unfortunately, there are many issues which may prevent the morphing segmented concept from becoming a viable wind turbine design concept for widespread use. The two most challenging issues are perhaps: 1) structural stresses due to high spar bending loads in the downwind direction at high aerodynamic loading conditions and 2) chord-wise and/or span-wise dynamic instability of the blade elements due to reduced system stiffness.

For the spar bending problem, use of tension cables (instead of the blade segment skin) to resist the stresses may be beneficial since cables are very mass-efficient in resisting pure tension loads. Carrying these stresses with the cable can alleviate the high compressive and tensile stresses which can build up on the inboard and outboard portions of a shell system in bending. By extending the rotating hub axial length, an additional cable system may be placed in front of and exterior to the blade. At extreme-scales (rotor diameters greater than 150 m), such cables will effectively have a small aerodynamic impact due to their extremely small relative size compared to blade chord lengths. One end of the cable can be fixed upstream of the hub and the other end connected to the outboard blade tip, and the outboard portion of the cable could be aerodynamically faired. This external cable would prevent excessive coning and help carry the downstream bending loads, along with (or instead of) the internal cable. Such an external cable would be similar to the concept used in suspension bridges, which are an appropriate structural load analogy for extreme-scale wind turbine systems. However, the socket junctions must be designed to accommodate very high local moments with low friction to accommodate morphing. As such, a detailed structural design is required to determine whether the segmented morphing concept is both feasible and practical.

Perhaps the most daunting of these is flutter instability which will be more problematic owing to the increased flexibility of the blade system. This is particularly true at extreme-scales for which flutter speed decreases due to increased coupling of the flap-wise and torsional modes (Hansen *et al.* 2006). Flutter instability can arise due to gusts, tower-mast wake effects, and wakes from nearby wind turbines and can lead to potentially damaging limit cycle oscillations and highly unsteady loading on the socket joints. One technique to address these oscillations is by controlling the tension of the blade cable through the use of a spring and damper system at the blade hubs. Possible control solutions may include passive nonlinear energy sinks (Lee *et al.* 2008). Other concepts being actively explored include the active pitch control systems of Wilson *et al.* (2008). As such, the control of flutter may significantly increase system complexity and weight of this segmented morphing concept which may eliminate some or all of the potential benefits discussed above.

In summary, the above issues may render the overall concept unsuitable even at extreme scales. It is recommended that future work focus on quantitative benefits and disadvantages of the morphing segmented concept using a quantitative system level basis. This will help determine its feasibility and whether detailed simulations and experiments are appropriate.

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