SAND2013-10747C

Definition of the National Rotor Testbed: An Aeroelastically Relevant Research-Scale Wind Turbine Rotor

Brian R. Resor, David C. Maniaci[1]
Sandia National Laboratories[2], Albuquerque, New Mexico, 87185

Sandia is designing a set of modern, research-quality blades for use on the V27 turbines at the DOE/SNL SWiFT site at Texas Tech University in Lubbock, Texas. The new blades will replace OEM blades and will be a publicly available resource for subscale rotor research. Features of the new blades do not represent the optimal design for a V27 rotor, but are determined by aeroelastic scaling of relevant parameters and design drivers from a representative megawatt-scale rotor. Scaling parameters and design drivers are chosen based two factors: 1) retrofit to the existing SWiFT turbines and 2) replicate rotor loads and wake formation of a utility scale turbine to support turbine-turbine interaction research at multiple scales. The blades are expected to provide a publicly available baseline blade design which will enable increased participation in future blade research as well as accelerated hardware manufacture and test for demonstration of innovation. This paper discusses aeroelastic scaling approaches, a rotor design process and a summary of design concepts.

Nomenclature

AEP	=	Annualized Energy Production
c	=	blade chord
C_d	=	sectional drag coefficient
C_l	=	sectional lift coefficient
LES	=	large eddy simulation
r	=	local rotor radius
R	=	rotor radius
RANS	=	Reynolds averaged Navier-Stokes equations
Re	=	$\rho Vc / \mu$; Reynolds number
SWiFT	=	Scaled Wind Facility Test site
V_{rel}	=	airfoil section air speed
V_∞	=	wind inflow speed
$VSVP$	=	Variable Speed Variable Pitch
α	=	angle of attack
λ	=	$\Omega R/V$; tip-speed ratio; TSR
Γ	=	aerodynamic circulation
Γ'	=	aerodynamic non-dimensional circulation

[1] Members of the Technical Staff, Wind Energy Technologies Department, PO Box 5800 MS1124
[2] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

ρ = air density
μ = air viscosity
ω_i = i^{th} structural natural frequency
$\tilde{\omega}_i$ = ω_i / Ω ; non-dimensional natural frequency
Ω = rotor angular speed

I. Motivation and Goals

The U.S. Department of Energy (DOE) Atmosphere-to-electrons initiative (A2e) and Sandia National Laboratories (SNL) are in the process of designing a modern, research-quality turbine blade set for use at the Scaled Wind Farm Technology (SWiFT) Facility at Texas Tech University in Lubbock, Texas. This new rotor will be a public resource that will accelerate important rotor innovation and turbine-turbine interaction research so that DOE can meet goals related to lowering the cost of electricity by increasing the efficiency of wind power plants. A subscale representative of current, and future, rotors is needed at SWiFT in order to accelerate this important research. The new Sandia rotor design is designated the National Rotor Testbed (NRT). The rotor concept features similar design drivers and technology found on modern multi-megawatt utility scale rotors. Specifically, it is focused on recreating the rotor loads and wake characteristics of a particular modern utility scale rotor.

The SWiFT Facility has been specifically designed and constructed to tackle the challenges of DOE's Turbine-Turbine R&D efforts, which aims to increase the performance and reliability of wind plants. The SWiFT facility is unique in that it utilizes turbines that are large enough to represent important physics relevant to utility scale machines, yet small enough to be extremely cost effective when compared to the megawatt scale counterparts.

The SWiFT facility currently features 1980’s era, Vestas V27 225kW turbines with 27m diameter rotors. While the aerodynamic and structural technologies used in the original rotors of the V27 enabled a cutting edge product in their own time, today’s modern turbines (1.5-3MW ratings with rotor diameters of 70-120m) take advantage of an additional 20+ years of wind energy rotor technology research. Today’s modern rotors are designed to a new level of optimal aerodynamic and structural efficiency. However, today’s rotors come with their own challenges: acoustics, controls, sensing, aerodynamics and structural dynamics.

In particular, the DOE A2e Initiative has set goals to understand the complex flow issues associated with modern rotors and wind farms. There is a very close coupling between the needs of the A2e Initiative, associated test and simulation campaigns and the new rotor design for SWiFT. It is envisioned that the NRT blades will be primarily used to study two phenomena in the near term: wake deficit recovery as a function of atmospheric conditions and turbine-turbine interaction effects due to wake impingement on a downstream rotor. Findings from turbine-turbine interaction research performed on these machines will be used to guide improvements in overall wind plant efficiency.

Figure 1: Scaled Wind Farm Technology Facility concept (left) and completed construction (right).

The concept thus far has been influenced by several industry partners in order to ensure its relevance as a small-scale version of large, modern rotors. The subscale nature of the NRT blades at SWiFT enables high fidelity measurements and sensing along with accurate physical simulation of large rotors at a physical size which is logistically simpler and perhaps an order of magnitude more cost effective than relying on equivalent megawatt-scale test facilities.

Aerodynamic and structural design information describing this rotor, as well as the SWiFT turbines, will be made publicly available at the conclusion of the project. In its role as an open source public resource, the NRT will provide a previously unavailable vehicle for public research at a scale which is physically relevant to solving today's cutting edge rotor innovation and turbine-turbine interaction challenges.

II. SWiFT Turbines

White, et.al. describe the SWiFT Facility in detail in a complementary 2014 AIAA paper [1] as well as through numerous online resources on the website: Ref.[2]. A FAST [3] model of the SWiFT turbines has been created to support the design of the NRT, as well as all other research activities at SWiFT. The model is currently in final stages of development and documentation. It will be made available to the public in order to support future research at the SWiFT Facility. Table 1 summarizes some important characteristics of the turbine and the model.

Table 1: Summary of OEM V27 FAST model parameters

		Remarks
Rating (kW)	225	SWiFT turbines rated up to 300 kW
Control	2-speed, collective pitch	SWiFT turbines are variable speed collected pitch
Tower height (m)	30	
Hub height (m)	31.5	
Rotor diameter (m)	27	
Airfoil family	NACA 63-200 series	
Maximum chord length (m)	1.285	
Blade length (m)	13	
Rotor solidity (%)	6.0	
Rated tip speed (m/s)	62	
Blade weight (kg)	600 (design)	660 (measured)
Blade material	Glass reinforced polymer (GRP) construction: box spar, skins with foam core, gel coat surface coating	
Rotor thrust limit (kN)	35	Estimated characteristic load based on extreme wind on flat side of parked blade
Blade root bending moment limit (kNm)	190	Estimated characteristic load based on extreme wind on flat side of parked blade
IEC Turbine Class rating at SWiFT	II-A	Rating for rotor retrofit at the SWiFT site

The OEM V27 machines operate with a 2-speed, variable (collective) pitch control scheme. Together, Vestas and Sandia developed and implemented a VSVP (collective pitch) control scheme for the SWiFT turbines. The new controls and generation approach enables higher rotor speeds as well as variable speed control in Region 2. The max power rating for the new generator is 300 kW, up from the OEM available 225 kW rating. More details of this conversion can be found in Ref.[1].

III. Functional Scaling for Turbine-Turbine Interaction Research

In Reference [5], Bottasso outlines a process for aeroelastic down-scaling of a megawatt-scale rotor to a wind tunnel sized rotor. The design of scaled aerodynamic models of wind turbines for wind tunnels is challenging because of the large scaling factors required for mapping a multi-MW wind turbine (rotor diameters in the vicinity of 100m) into the necessarily small wind tunnel model (rotor diameters of a few meters). This in turn implies large differences in the Reynolds number. Bottasso uses special airfoils were chosen to represent the desired aerodynamic characteristics at the much lower Reynolds number. Structural dynamics can be tuned to match the non-dimensional characteristics of the larger machine. In the case of a small wind tunnel model, rotor operating speeds may have to be limited due to absolute constraints or controls bandwidths. One can end up in a situation where one scaling parameter is compromised due to physical limitations of the model and then several other scaled parameters also have to find a compromised operating point.

The 27-meter rotors at SWiFT represent a nice middle ground between the highly controlled environment of a wind tunnel and the full physical representation of an actual full-scale megawatt scale machine. The size of the SWiFT turbines are such that they are not subject to some of the limitations of a smaller wind tunnel model.

There are numerous drivers that can determine the design of a subscale rotor. Following is a list of possible scaling parameters that have been identified in the course of this work:

- Tip speed ratio
- Reynolds number
- Froude number
- Mach number
- Locke number
- Non-dimensional natural frequencies
- Non-dimensional time
- Wake meandering behavior
- Downstream flow character
- Characteristic size of inflow and downstream turbulence
- Blade geometry
- Thrust force distribution
- Thrust and power coefficient distributions
- Lift coefficient distribution
- Rotor solidity
- Airfoil thickness distribution and blade thickness distribution
- Distribution of axial and tangential induction factors
- Tip deflection
- Bend-twist coupled dynamics of blades
- Blade architecture

Not every scaling relationship can be maintained for any given subscale rotor design. The functional intent of the subscale rotor must be well defined before the long list of scaling parameters can be narrowed down to those that will drive the design.

Following are the current high level design goals for the NRT:

- retrofit to the existing SWiFT turbines and
- replicate rotor loads and wake formation of a utility scale turbine to support turbine-turbine interaction research; i.e. produce wakes of realistic geometry, velocity deficit and turbulence intensity.

Detailed design requirements for the NRT come from the high level goals, listed in order of expected importance:

1. Maintain rotor loads within allowable limits for the SWiFT turbines
2. Recreate the shape of the circulation distribution along the rotor span
3. Match the tip speed ratio of the full scale rotor
4. Match the tip velocity of the full scale rotor
5. Match the Campbell diagram in the lowest frequency range
6. As well as possible, match the delta between $C_{l,max}$ and design C_l values along the span of the blade.

The NRT is not a simple geometric scaling of a large rotor to a small rotor. The scaling process described in this paper is termed *functional scaling*. The scaling work of Bottasso is rigorous and is derived with assistance from Buckingham Pi Theorem. The process does a very nice job of sorting out the optimal compromise between several scaling parameters (TSR, Re, Fr, Ma, Lo, omega and tau) for a rather large change in scale from a 90 meter rotor to a 2 meter rotor. In many ways, scaling to the modest NRT scale is a more feasible problem. The change in Reynolds numbers is not as dramatic. Within the smaller extent of scaling performed here, there is perhaps more leeway in the rotor design – leeway that can be used to match certain rotor characteristics to a higher degree. Perhaps not only can scaling parameters be satisfied but also arrays of scaling parameters, such as rotor circulation distribution, as described below as Requirement #2.

Still, this paper will show that the NRT design can end up quite constrained. It is crucial to gather feedback from the research community on the relative importance of the chosen scaling goals so that the final scaled metrics are the most relevant.

A. Requirement #1, Maintain Allowable Rotor Loads

The retrofit rotor must not produce loads that fall outside an allowable envelope for the existing turbine. Or, if the allowable loads are exceeded, the project must take steps to ensure the safe operation of the machine. As more is asked of a rotor design, the more the rotor loads can increase.

B. Requirement #2, Circulation Distribution

It is envisioned that the NRT blades will be used to study two important phenomena: wake deficit recovery as a function of atmospheric conditions and turbine-turbine interaction effects due to wake impingement on a downstream rotor. Factors influencing these effects are the wake structure, stability, and the wake's interaction with turbulence induced by the atmospheric boundary layer. High-fidelity CFD solutions of rotor wakes indicate the importance of the initial, near wake structure in determining wake stability and deficit recovery [6]. The near-wake structure is created by and dependent upon the blade circulation distribution. Therefore, this is one of the scaled blade design drivers.

A sensitivity study is being performed to quantify the dependency of the near- and mid-wake on the blade circulation distribution. The study will guide the required accuracy of subscale blade circulation distribution. This study has several parts, one of which is a sensitivity study of the wake deficit at several downstream locations on the blade circulation distribution in uniform inflow. A free-wake vortex method is being utilized for this study, as it can predict the wake deficit with a much lower computational expense than other methods, such as RANS or LES. An actuator line based LES solution of the wake deficit with a uniform inflow is also being performed for direct comparison to the free-wake vortex method predictions. The LES method will also be used to study the sensitivity of the wake deficit predictions on various atmospheric inflow conditions, the results of which will be used to access the limitations of using a uniform inflow and of the free-wake vortex method predictions.

An example wake deficit prediction from the free-wake vortex method simulation is presented below in a steady, uniform inflow. The predictions are for the NREL 5MW reference model, as it is publicly available, although this turbine will not be used in the final blade scaling and sensitivity studies. An image of the iso-surface of velocity magnitude of the rotor wake is shown in Figure 2 from one time step of a free-wake vortex simulation of this turbine.

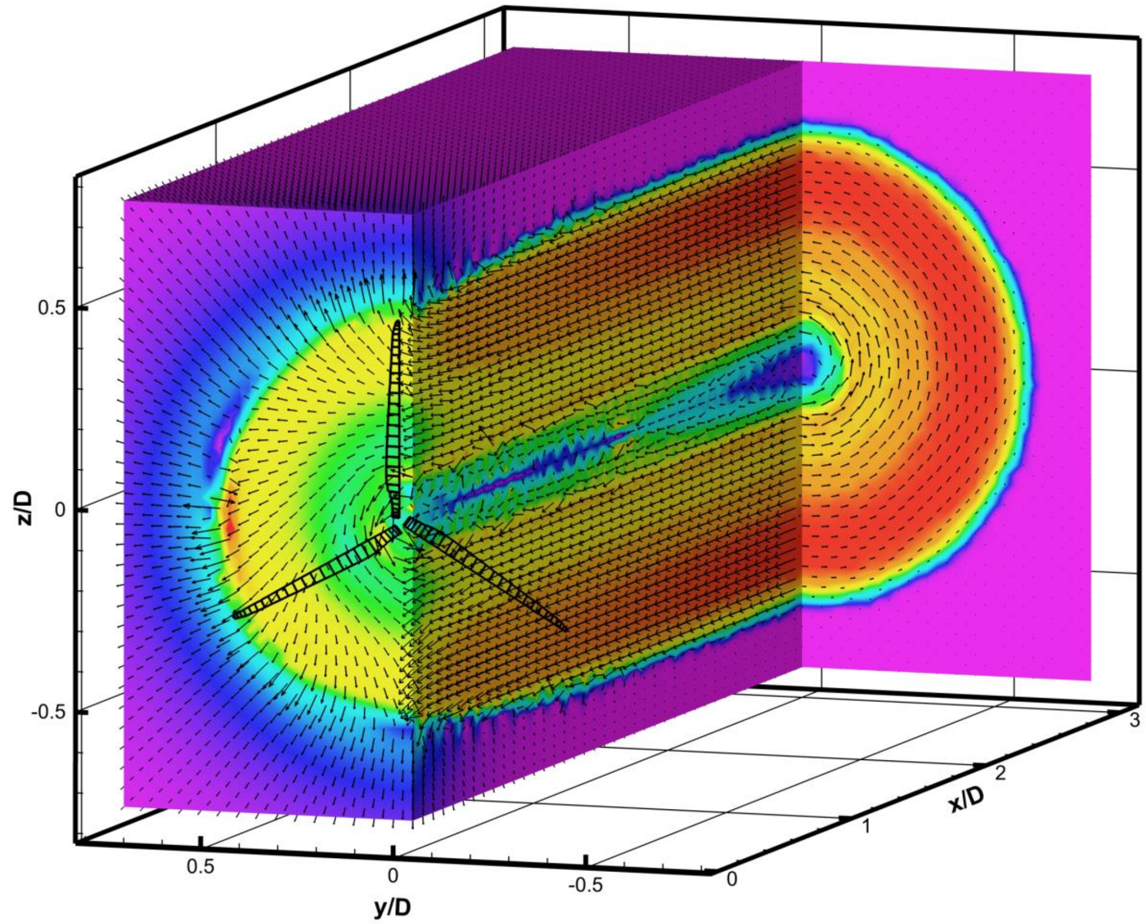

Figure 2: Induced velocity in the rotor wake 0.5-2 diameters downstream of the rotor plane. Velocity vectors are projected in the planes shown.

A slice through the centerline of the wake at one time step is shown in the left side of Figure 3, as well as wake velocity deficit distributions at several downstream locations. The wake velocity deficit was time-averaged over one rotor revolution, the results of which are shown in the right side of the Figure 3.

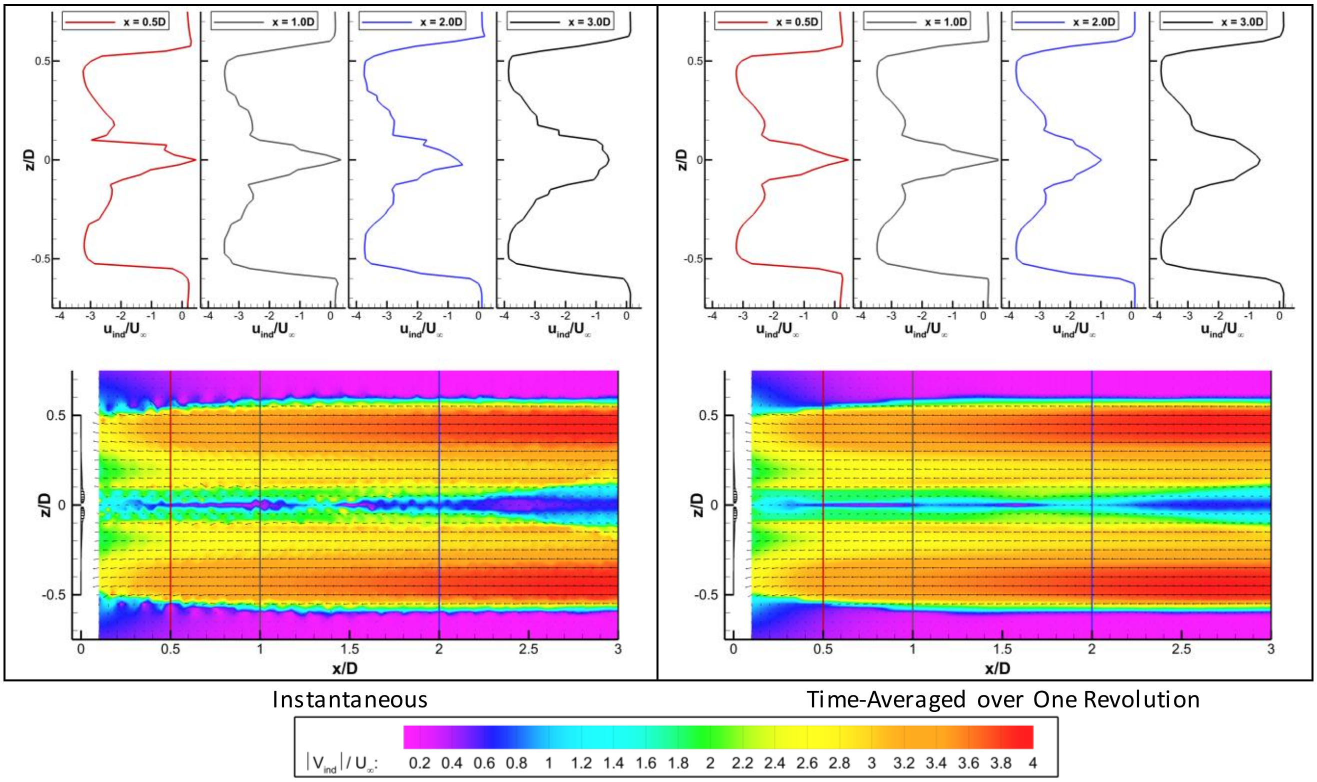

Figure 3: Comparison of the instantaneous and time-averaged wake induced velocity from 0.1 to 3 rotor diameters downstream of the rotor plane.

A non-dimensional form of the circulation is defined here in order to enable comparisons between various rotor scales:

$$\Gamma' = \frac{C_l}{2} \frac{V_{rel}}{V_\infty} \frac{c}{R} \qquad \text{Eq.(1)}$$

Figure 4 illustrates examples of circulation distribution for three different rotors: an estimated 27 meter rotor at design point (in Region 2) as well as two fictional examples which are provided for illustration. Computation of parameters in the circulation distribution were obtained using WT_Perf [7]. Loading of the 27 meter rotor is consistently high along the entire length of the blades, with the exception of the tip, where tip losses dictate that the loading decrease. The two fictional examples show how other blade designs may differ from one another, especially near the tip. Blade loads on the outboard regions of blades are often reduced either intentionally by a designer, or through the use of a rotor design optimization process. Primarily, outboard loads are reduced for two reasons: 1) to unload this region of the blade in an effort to improve aero-acoustic performance or 2) to unload the blade in an effort to move rotor loads inboard. The second motivation can be especially common in design of retrofit blades, i.e. designing a longer blade to install onto an existing turbine nacelle design.

After analysis of several types of rotors, concept rotors and actual rotor hardware, Sandia believes that a realistic target for a circulation distribution resembles the red dashed curve in Figure 4. This is a distribution indicative of a rotor with outboard design intents which achieve effective acoustics and loads mitigation. The overall elevated values of the red dashed curve may be indicative of a rotor that is sized appropriately for the rest of the turbine, unlike the green dashed curve in Figure 4 which resembles the NRT Concept 1a design found later in this report.

The red curve in Figure 4 is used as a preliminary design target for NRT Concept 1b later in this report.

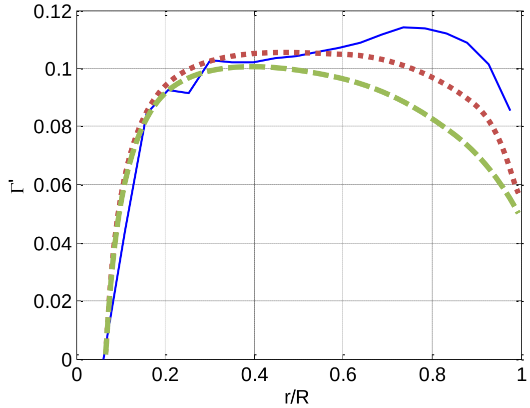

Figure 4: WT_Perf estimated non-dimensional circulation distribution for Region 2 operation of a 27 meter rotor (blue); Other conceptual rotor designs showing decreased outboard blade loading (red and green dashed)

C. Requirement #3, Tip Speed Ratio

Tip speed ratio captures many aspects of a rotor design as well as its wake geometry. It is a fairly straightforward parameter to include and to successfully match during a rotor redesign. Many modern rotor designs operate in Region 2 at TSR's in the range of 8 to 9.

D. Requirement #4, Tip Velocity

Land-based wind project development has constrained turbine designs to operate at blade tip velocities historically in the range of 75-80m/s. In the drive to fit longer blades onto existing turbine systems, blade tip velocities are creeping up, often into the vicinity of 90 m/s. The tip velocity constraint arises from blade tip aero-acoustic noise generation. There is a rather delicate tradeoff in system benefits when tip velocities are increased. Higher tip velocities are beneficial for certain system loads, but detrimental to others. The topic of rotors which can operate quietly at high tip velocities is an area of research that the NRT will easily support, if the NRT tip velocity can be placed in a range that is relevant to the megawatt scale.

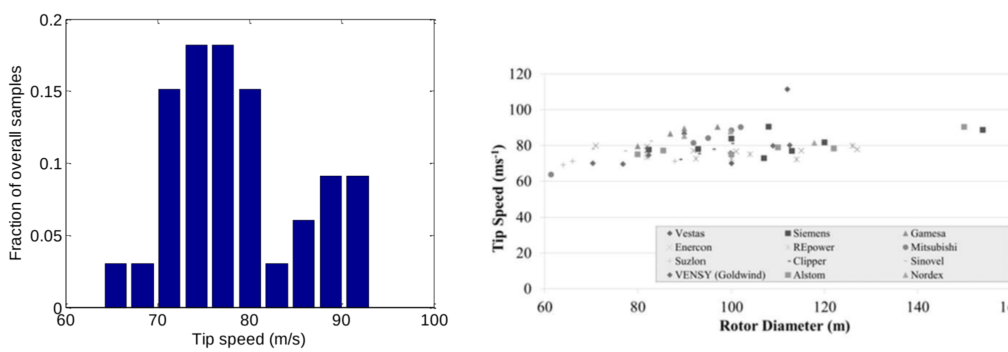

Figure 5: a) Estimated tip speeds for a collection of currently available turbine models (Data sourced from current online OEM literature) and b) tip velocities shown with rotor diameter (Ref.[8], Figure 2).

Industry feedback thus far guides the NRT design toward tip velocities of at least 73-75 m/s, possibly as high as 80 m/s. The upper operating speed of a SWiFT rotor is limited by a tower mode measured at 1 Hz (60 rpm). Therefore, the upper limit on rotor speed is set safely at 60 rpm minus 10%, or 54 rpm. The lower rotor speed is limited by the rated generator torque for the updated generator: 1610 Nm for power production of 225 kW; the lower rotor speed limit for 225 kW generation is 47.8 rpm. A rotor speed midway between the upper and lower limits is 50.9 rpm. The NRT design concepts shown in this report assume a rated rotor speed of 50.9 rpm.

High tip velocities can be achieved if the rotor radius is increased. Figure 6 computes rotor speed, generator speed, generator torque and tip velocity for maximum rotor speeds:

- Figure 6, Row 1: generation of 225 kW at rated torque leads to rotor speed of 47.8 rpm;

- Figure 6, Row 2: operation at max allowable rotor rpm leads to tip velocity of 82 m/s.
- Figure 6, Row 3: operation in the middle (50.9 rpm) achieves a tip speed of 77.3 m/s.

Inputs:		
Gearbox ratio	27.9	-
Rotor radius	14.5	m
Power output	225	kW

per-D spacings	
SNL1-SNL2	4.7
Vestas-SNL2	5.6

	Rotor RPM	Generator RPM	Generator torque (Nm)	Tip velocity (m/s)	
1	47.8	1335	1610	72.6	@ generator torque limit
2	54	1507	1426	82.0	@ rotor speed limit
3	50.9	1421	1512	77.3	operation in middle ground

Figure 6. Speed, torque and tip velocity computations for a proposed NRT rotor radius of 14.5 meters.

Increased tip velocity due to increases in rotor radius come at a cost. First, the SWiFT site was carefully designed to take advantage of specific turbine to turbine spacing. The spacing is measured in terms of 27 meter rotors. There are a total of three turbines at the site: a Vestas machine and two Sandia machines (SNL1 and SNL2). The nominal spacing from SNL1 (upwind) to SNL2 (downwind) is five rotor diameters. The nominal spacing from the Vestas machine (upwind) to SNL2 (downwind) is six diameters. Modification of the rotor diameter changes the effective per-D spacing of the turbines. Second, an increase in rotor radius results in increased aerodynamic loads on the turbine. Third, an increase in tip speed, even done independently of rotor size increase, results in increased rotor loads. Care must be taken to design a rotor that can meet design Requirements #2-6 without failing Requirement #1.

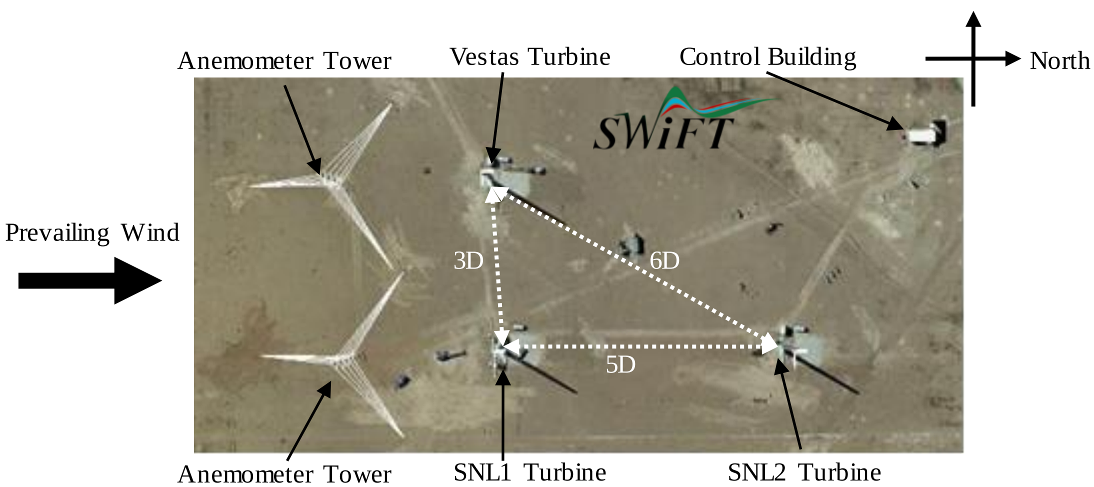

Figure 7: SWiFT layout with intentional turbine spacing based on 27 meter rotors

E. Requirement #5, Structural Dynamics

The subscale design will also represent the basic structural dynamics of the full scale rotor. Many of the turbine loads and associated controls are synced with the rotor revolutions and with structural dynamic frequencies. In order to represent dynamic response and control of the full scale turbine, we would try to scale the structural frequencies together with the rotor speed. Because the rotor speed for smaller turbines is higher than for larger turbines, the frequencies need to be higher in order to capture the same response character given the expected forcing. Luckily, scaling laws natural are in favor of this from the outset. The blade layup will be tuned in order to meet these goals.

F. Requirement #6, Lift Coefficient Delta

No aerodynamically scaled rotor is complete without consideration of Reynolds numbers. A key advantage of the SWiFT machines is that they are capable of flying rotors which are not only small and cost-effective, but also bring the Reynolds numbers of the rotor into a range that is relevant for research on megawatt scale rotors (greater than 2 million). Figure 8 shows the distribution of Reynolds numbers for two rotors: a 27 meter rotor and a larger megawatt scale rotor. Reynolds numbers at 75% span are different but it is possible that the same airfoils from a large baseline rotor can be used in its scaled down counterpart because the Reynolds numbers are maintained largely above 1 million.

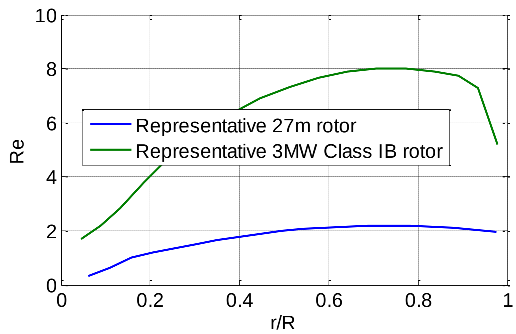

Figure 8: Approximate Reynolds numbers along the rotor span for two rotors.

It is also important to understand the potential effects of the change in Reynolds number when scaling is done. Figure 9 illustrates the possible differences in polar data experienced by the same airfoil at two different Reynolds numbers. The change in Reynolds number has several effects on the aerodynamic operation of the blade. As Reynolds number decreases, the linear lift curve slope stays the same but the maximum lift coefficient for the airfoil decreases. At lower Reynolds numbers, profile drag increases and the maximum lift-to-drag ratio decreases. The design lift coefficient, typically chosen at best lift-to-drag, can change. If scaling is taken too far, the airfoil performance characteristics of the original rotor may be no longer valid and the rotor design (airfoils, chord and twist) may be suboptimal.

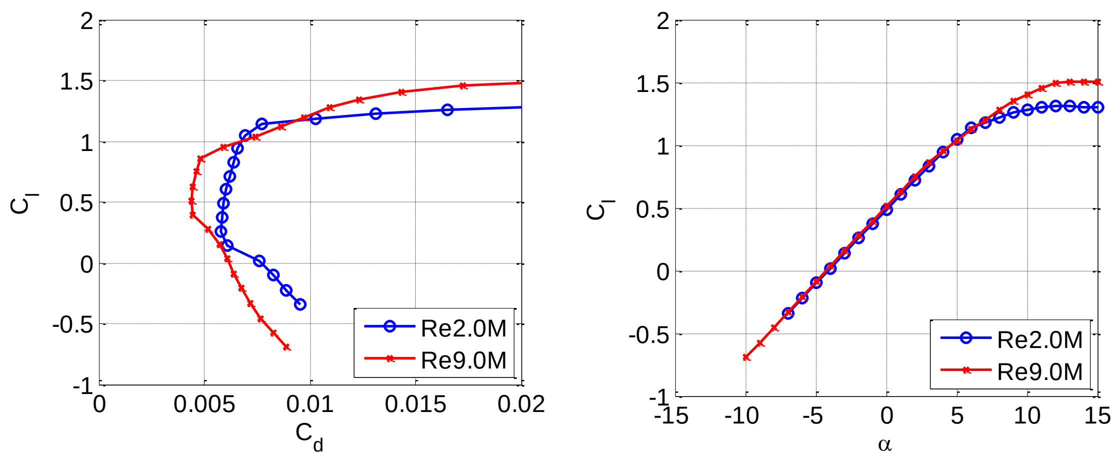

Figure 9: Example Reynolds number effects on a NACA 64-618 airfoil [9]. Data shown are generated with RFOIL.

Rotor performance is also affect by the difference between design C_l and airfoil C_{l_max}. A wind turbine rotor operating in steady flow with no yaw error and no rotor tilt will operate at a constant angle of attack at its design lift coefficient until wind speed increases into Region 2.5 and then Region 3 operation where the blades are pitched to shed loads. A realistic turbine operates in turbulent wind and experiences gusts that drive the angle of attack above and below the design point. Airfoils stall when angles of attack exceed the stall angle near the maximum lift coefficient. Additionally, peak loads at angles of attack near stall are driven by the maximum lift coefficient at the higher angles, as well as dynamic stall effects. At angles of attack near and above stall, the maximum lift coefficient is determined by both the airfoil C_{l_max} and dynamic stall effects. It is advantageous, albeit challenging, to include these effects in the design of a scaled rotor.

The result of decreased Reynolds numbers on the smaller rotor has caused an overall decrease in maximum lift coefficient. The consequences of decreased Reynolds number are most prominent at the root of the blade. In this region, the operating lift coefficient can be quite high, likely very close to the maximum lift coefficient of the airfoil. If not carefully designed, this setup will cause the inboard region of the scaled blade to operate consistently in a stalled state. Inboard stall can have consequences on the outer portions of the blade because of spanwise flow and induced velocity effects along the blade. This scenario should be avoided.

G. Final Scaling Metrics

Rotor designs shown here are preliminary. Scaling targets are conceptual. They do not emulate a specific megawatt-scale rotor at this point. Upon initiation of NRT design Concept 2 (Table 2), a single full scale rotor will be analyzed and its characteristics will provide metrics to guide a final conceptual rotor design. The choice of full scale rotor is a decision to be made by the larger research community, especially the DOE A2e participants.

IV. NRT Design Concepts

The NRT is expected to evolve through several design stages prior to manufacture and flight. Table 2 summarizes the design concepts. Concepts 1a and 1b are the subject of this paper. Concepts 2 and 3 will occur in the near future and will incorporate lessons learned from early concepts as well as feedback from the research community.

Table 2: Summary of NRT design concepts

NRT Concept	Description	Status
1a	Rotor designed by Wetzel Engineering, Inc. in partnership with Sandia. Primary design drivers include • SWIFT turbine rotor load constraints, • increased rotor diameter (29m up from 27m), • increased tip velocity (78 m/s up from 62 m/s) • maximize turbine AEP • use of modern airfoils (DU-series) • approximate match of desired TSR	Completed October 2013
1b	Rotor concept designed by Sandia. Primary design drivers include • match desired non-dimensional circulation • match desired TSR • increased rotor diameter (29m up from 27m), • increased tip velocity (78 m/s up from 62 m/s) • use of modern airfoils (DU-series)	December 2013
2	Incorporate lessons learned from 1a and 1b. Reprioritize the scaling drivers (rotor radius, tip velocity and loads) to arrive at a design that meets scaling criteria and meets allowable loads for the SWiFT turbines. Seek formal feedback from the research community in the form of a design review.	Summer 2014
3	Incorporate formal feedback on concept 2 into concept 3. The final design concept will move forward into manufacture and flight tests.	Fall 2014

H. NRT Concept 1a

Wetzel Engineering and Sandia together created a 29 meter rotor design that meets the rotor loads constraints of the existing SWiFT turbines (Requirement 1) and tip velocity target (Requirement 4). Sandia guided the blade design toward an increased rotor diameter (29m) to promote higher tip velocities. The rotor design process was similar to typical retrofit blade designs.

Details of the rotor design are documented in several reports to Sandia. The outcome of the design process was a rotor concept that can be flown on the SWiFT turbines, but perhaps falls short of the goal to match a target circulation distribution. Figure 10 shows the target and actual achieved circulation distribution for Concept 1a. The red curve in Figure 4 is used as a circulation for comparison to NRT Concept 1a. The outboard portion of the blade is heavily unloaded to meet rotor load constraints of the SWiFT turbine. This design shows that increasing design variables for rotor size and tip velocity, together, lead to a rotor with loads that are quite high compared to the OEM rotor. Further work to understand the tradeoffs between rotor size, speed, and loads is needed.

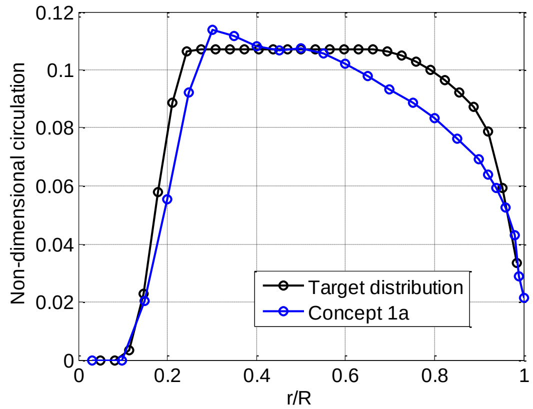

Figure 10: Design concept 1a circulation distribution

I. NRT Concept 1b

Design Concept 1a shows that matching scaling criteria while maintaining rotor loads at a reasonable level is a challenge. Concept 1b is meant to explore the possibility of designing a rotor that meets Requirements 2 (circulation distribution) and 3 (TSR) while ignoring Requirement 1 (rotor load constraints). The goal of design concept 1b is to bound the problem; to understand what is required of the turbine, in terms of rotor loads, to meet the scaling criteria Requirements 2, 3 and 4 (tip velocity).

Several existing, publicly available blade and rotor analysis tools have been assembled such that rotor designs may be optimized based on a variety of objectives. Typical new or retrofit rotors designs are optimized such that they achieve the lowest cost of wind energy, that is, lowest capital cost (blade cost) for the highest energy capture. References [10, 11] illustrate examples of rotor and turbine system designs that are designed for low cost of electricity. The NRT design does not aim to maximize energy capture. Instead, it aims to match the specified rotor characteristics described above.

Reference [10], "Effects of Increasing Tip Velocity on Wind Turbine Rotor Design," describes in detail the tools used to perform an aero-structural rotor optimization. The basic components are as follows:

- HARP_Opt v2.00.00 [12] is used to manage the multiobjective optimization of the rotor. Rotor mass is minimized while rotor AEP is maximized. A Pareto front of design candidates shows designs that are most effective. Design variables include chord distribution, twist distribution, blade thickness distribution, and spar cap thickness distribution. Representation of the spar cap in HARP_Opt is a capability added by Sandia in order to more accurately represent the blade structure.
- NuMAD v2.0 [13] has been improved for this work. NuMAD now utilizes a new, parametric representation of the entire blade geometry, materials, and layup. The parametric framework enables easy integration of blade designs with optimization tools. The NuMAD blade object was implemented in HARP_Opt in order to improve the structural realism during aero-structural optimization.
- Co_Blade v1.20.00 [14] is used for structural computations within the HARP_Opt framework. A conversion from the NuMAD blade object format into Co_Blade format enables all three tools to work together.

Finally, modifications to the HARP_Opt objective function enable the NRT Concept 1b shown here. Rather than optimizing a rotor for lowest mass and highest AEP, this design seeks a rotor with lowest mass and lowest error between actual and target scaling metrics. Metrics used in the objective function for these designs are as follows:

- difference between actual and target distribution of non-dimensional circulation and
- difference between actual and target TSR of 8.5.

The red curve in Figure 4 is used as a preliminary design target for NRT Concept 1b.

Blade thickness distribution and airfoil distribution remain the same as NRT Concept 1a. Blade chord distribution, twist distribution and spar cap thickness distribution are used as design variables. The results of the multiobjective optimization are shown in Figure 11. A lower objective score equates to a smaller difference between actual and target values. Three design candidates from the Pareto front are chosen for closer examination: one high mass and close match of target criteria, one low mass and lesser match of target criteria and one intermediate. Note that blade mass is an indicator of rotor loads. Higher mass is indicative of a larger spar cap, which is demanded by the combination of higher rotor loads along with an unchanging tip deflection constraint.

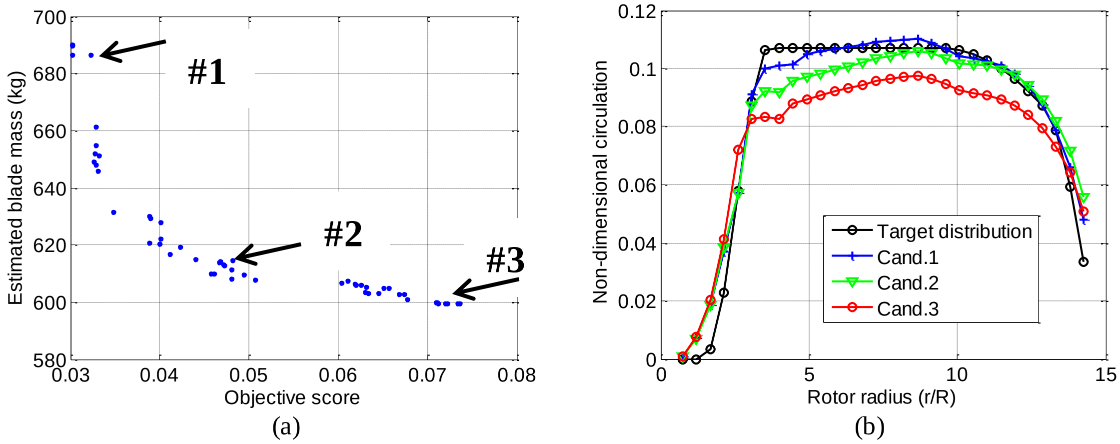

Figure 11: a) Pareto front of design candidates for NRT Concept 1b and b) NRT Concept 1b non-dimensional circulation distributions

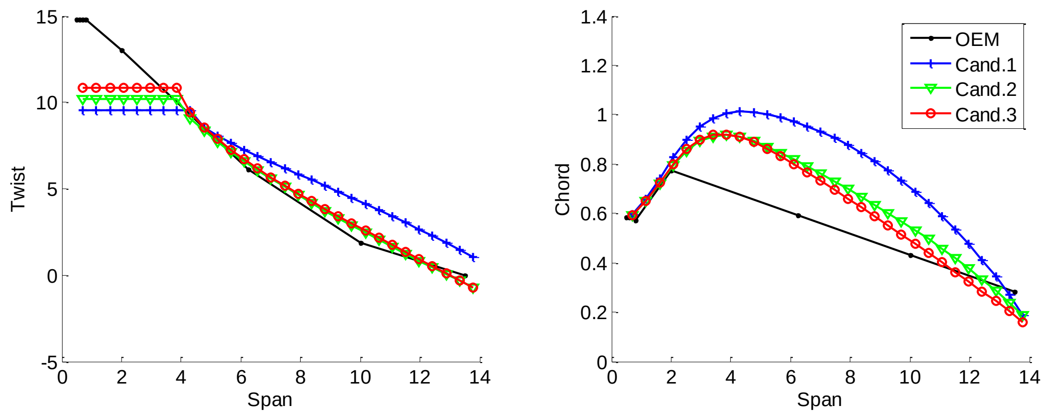

Figure 12: NRT Concept 1b twist and chord distributions

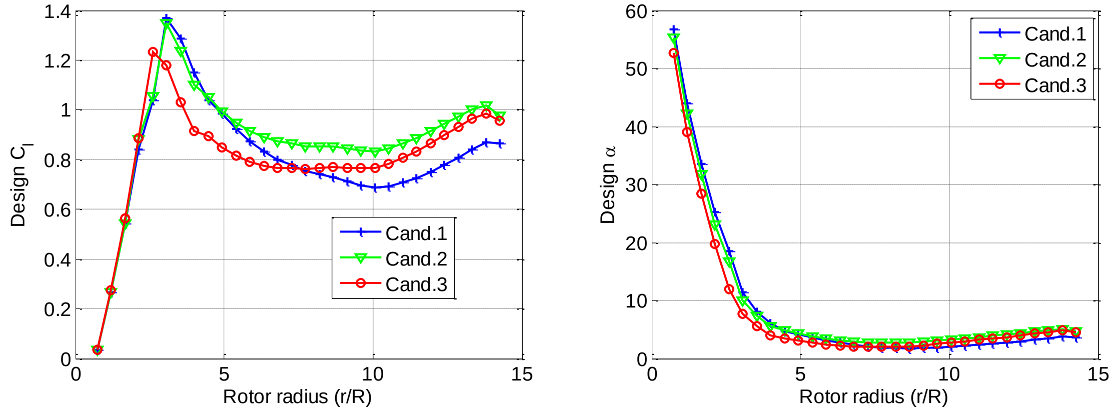

Figure 13: NRT Concept 1b C_l and alpha distributions at design point

Unlike NRT Concept 1b, these rotors were designed with permission to exceed allowable rotor loads. Rotor loads required to achieve these design goals are quite high. Higher loads are especially affected by the drive to operate at increased tip velocity using a rotor that is larger than the OEM rotor (29 m versus 27 m). Table 3 summarizes the steady rotor loads. Asterisks in Table 3 are a reminder of the fact that these computed loads are only for steady operation under normal conditions. A next step in the design of these rotors requires aeroelastic simulations to estimate the actual loads experienced during important design load cases such as normal and extreme turbulence, extreme winds in a parked configuration, and extreme gusts.

The margin between maximum allowable thrust loads (Row 0) and steady loads (Rows 1-3) is rather small. Further investigation of loads during dynamic load cases will show that the rotor design is not feasible within the estimated loads envelope.

Table 3: Summary of rotor loads for NRT Concept 1b design candidates

Row		Maximum rotor thrust (kN) Characteristic value	Maximum blade root flapwise bending moment (kN) Characteristic value
0	Requirement	< 35	< 190
1	Cand.1 *	31.5	92.7
2	Cand.2 *	30.1	89.5
3	Cand.3 *	27.9	81.8

* Estimated loads are based only on steady loading. Dynamic load cases need to be considered in order to estimate operating loads.

V. Conclusions and Future Work

This paper has shown how different design approaches can arrive at rotors to achieve different goals. The first design approach shows how to arrive at a rotor that can fly within the rotor load constraints of the SWiFT turbines, but at the cost of excessively unloaded blades. The second design approach show how to arrive at a rotor that can meet unique rotor load and performance characteristics, but at the cost of high rotor loads which exceed allowable limits. These two designs demonstrate some of the boundaries around what may be achieved with respect to design requirements 1-6 listed above.

Rotor loads for the larger rotor, with higher tip velocities, are high enough to limit other design goals. Tradeoffs between allowable rotor loads for the SWiFT turbines and proposed design requirements will be explored. There are perhaps two approaches available to move forward:

- Increase the allowable SWiFT turbine rotor loads envelope. Current constraints are only estimates. Less conservative estimates of rotor load constraints will allow the design to achieve more.
- Decrease the proposed rotor diameter from 29 meters to the original 27 meters. The SWiFT site was originally designed for 27 meter rotors. The rotor diameter increase had been suggested as a means to achieve higher tip velocities. If higher tip velocities are not a high priority, then the rotor loads may decrease dramatically.

It is critical to consider whether the proposed scaling requirements are the best possible set. Feedback from the wind energy research community, in general, will drive these decisions.

Additional work to quantify the effects of blade designs on wake characteristics is being done. The near-wake structure is created by and dependent upon the blade circulation distribution. In order to study the effect of blade design parameters on the near-wake velocity field, a sensitivity study is being performed using free-wake vortex method. The method allows for the relatively fast computation of wake induced velocities as a function rotor blade circulation. Part of this on-going work includes high fidelity LES simulations of the same rotor wake for direct comparison to the wake deficit predicted by the free-wake vortex method. These simulations will direct the future direction of the A2e initiative efforts as well as final NRT rotor design requirements.

VI. Acknowledgements

The authors would like to thank Ken Lee, Amool Raina and Kyle Wetzel (Wetzel Engineering, Inc) for their wealth of knowledge on rotor design and for their work to define the initial NRT rotor design concept.

VII. References

1. White, J., Berg, J., Bryant, J., LeBlanc, B., Maniaci, D. C., Naughton, B., Paquette, J., and Resor, B. R. "Scaled Wind Farm Technology Facility Overview " *AIAA SciTech: 32nd ASME Wind Energy Symposium*. National Harbor, Maryland, 2013.
2. "Sandia National Laboratories: Scaled Wind Farm Technology (SWiFT)," http://swift.sandia.gov. Accessed on December 9, 2013.
3. Jonkman, J. *NWTC Design Codes FAST*. (v7.01a) http://wind.nrel.gov/designcodes/simulators/fast/. December 3, 2012.
4. "Static proof load testing of the Sandia and Vestas SWiFT V-27 wind turbine blades," National Renewable Energy Laboratory NWTC: 2012.
5. Bottasso, C. L., Campagnolo, F., Croce, A., and Maffenini, L. "Development of a wind tunnel model for supporting research on aero-servo-elasticity and control of wind turbines," *Paper presented at the 13th International Conference on Wind Engineering, Amsterdam, The Netherlands*. 2011.
6. Ivanell, S., Mikkelsen, R., Sørensen, J. N., and Henningson, D. "Stability analysis of the tip vortices of a wind turbine," *Wind Energy* Vol. 13, No. 8, 2010, pp. 705-715.doi: 10.1002/we.391
7. Platt, A. *NWTC Design Codes WT_Perf*. (3.0.00a-adp) http://wind.nrel.gov/designcodes/simulators/wtperf/. November 26, 2012.
8. Keegan, M. H., Nash, D. H., and Stack, M. M. "On erosion issues associated with the leading edge of wind turbine blades," *Journal of Physics D: Applied Physics* Vol. 46, 2013.doi: 10.1088/0022-3727/46/38/383001
9. Timmer, W. A. "An overview of NACA 6-digit airfoil series characteristics with reference to airfoils for large wind turbine blades," *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*. AIAA, Orlando, Florida, 2009.
10. Resor, B. R., Maniaci, D. C., Berg, J. C., and Richards, P. "Effects of Increasing Tip Velocity on Wind Turbine Rotor Design," Sandia National Laboratories: SAND2013-XXXX, 2013 [draft].
11. Dykes, K., Resor, B. R., Platt, A., Guo, Y., Ning, A., King, R., and Petch, D. "Effect of Tip Speed Constraints on Optimized Design of a Wind Turbine," National Renewable Energy Laboratory: NREL-XXXX, 2013 [draft].
12. Sale, D. C. *NWTC Design Codes HARP_Opt*. (v2.00.00) http://wind.nrel.gov/designcodes/simulators/HARP_Opt/. October 10, 2013.
13. Berg, J., Resor, B. R., Owens, B. C., and Laird, D. *Numerical Manufacturing and Design Tool (NuMAD) for Wind Turbine Blades*. (v2.0) http://energy.sandia.gov/?page_id=2238.
14. Sale, D. *Co-Blade v1.20.00*. https://code.google.com/p/co-blade/.