Effects of Increasing Tip Speed on Wind Turbine Rotor Design

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Goals of Tip Speed Investigation

"If we invent quiet blades, then we could spin the rotor faster which enables lighter, cheaper gearboxes, less nacelle weight, less tower weight, overall cheaper turbines and lower cost of electricity!" –the hypothesis

The full problem of wind turbine system optimization is complex. Focus on investigation of tip speed was helpful in that it

1. demonstrated a preliminary rotor optimization framework on a relatively simple multidisciplinary design problem and
2. provided a preliminary quantitative assessment of tip speed increase effects to prioritize research investments.

Background

- Modern land-based wind turbine rotors operate at tip velocities up to 75–80 m/s
- The speed constraints are attributed by many to noise constraints.
- Potentially higher rotor speeds lead to lower gearbox torque, lighter weight gearboxes, and cheaper turbine systems. Right?
- Actually, for high speed operation, changes in rotor loads can have a strong effect on the sizing and cost of other components in the system.
- The magnitude of these costs and benefits are not well quantified.

Presentation Goals

This presentation focuses on

- System level observations, not detailed design—detailed rotor design can be found in Sandia Report SAND2014-3136.
- How the interaction with the system requirements helped to produce a better rotor for the system even though it wasn't the rotor we were expecting at thle beginning.

Acknowledgements

This work was done as a joint effort between Sandia and NREL and is documented in a larger report:
"Effect of Tip-Speed Constraints on the Optimized Design of a Wind Turbine," NREL/TP-5000-61726

NREL

- The Systems Engineering Team (Dykes, et.al.)
- Danny Sale, HARP_Opt

Sandia

- David Maniaci, Rotor Aerodynamics
- Jon Berg, NuMAD
- Phillip Richards, Tool integration

DOE Wind and Water

- Shreyas Ananthan, Rotor Design

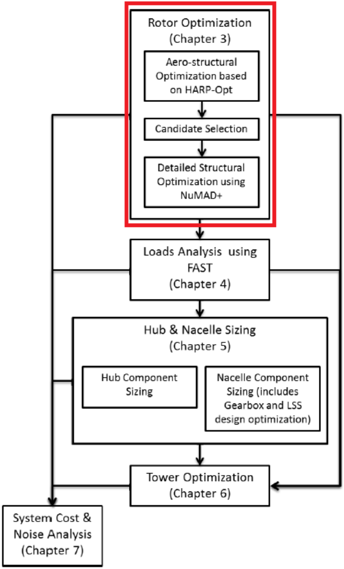
Process Flow

Three designs were created

- 1 normal speed (80 m/s) design
- 2 high speed (100 m/s) designs

Notes

- Rotor design combined capabilities of HARP_Opt, NuMAD, and CoBlade.
- Blade initiated with NREL 5MW reference (airfoil polars and balance of turbine)
- Layup initiated with Sandia 61.5 m reference (fabrics and material properties)
- FAST/AeroDyn was used to evaluate designs w.r.t. IEC loads cases.



(Taken from NREL Tip Speed Study Report)

Aero-Structural Design Variables

20 total design variables were available to the multi-objective genetic algorithm.

- 5 points shaped the entire chord distribution
- 5 points shaped the entire twist distribution
- 8 airfoil locations; a variable represented airfoil location for each of the following airfoil thicknesses: 18, 21, 21, 25, 25, 30, 35 and 40%
- 2 points shaped the distribution of materials in the spar cap

Aero-Structural Objective Function

The genetic algorithm used a multi-objective fitness function $F(x)$ to assess the quality of the blade design represented by the set of design variables.

$$F(x) = [F1(x), F2(x)] \tag{1}$$

The two dimensions of the fitness function were as follows

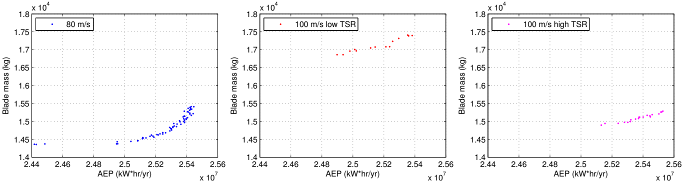
$$F1(x) = AEP(x) * (-1) \tag{2}$$

$$F2(x) = M(x) * P \tag{3}$$

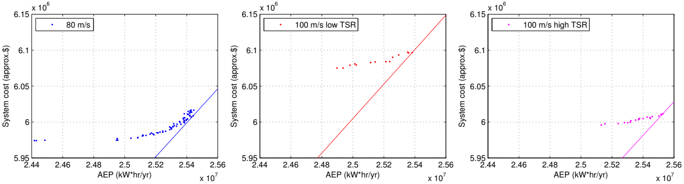
$$P = \begin{cases} \frac{\delta(x)}{\delta_{target}}, & \text{if } \delta(x) > \delta_{target} \\ 1, & \text{otherwise} \end{cases} \tag{4}$$

Aero-Structural Optimization Results

Approximately 30,000 designs were evaluated for each rotor (200 generations each with a population of 150).

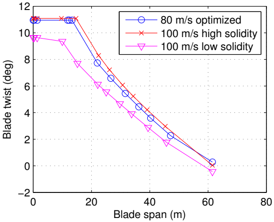


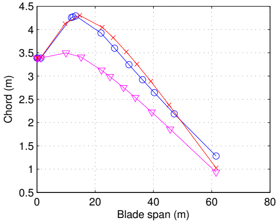
Pareto fronts showing the sets of noninferior designs. Points shown only for designs that meet tip deflection requirement, $P = 1$

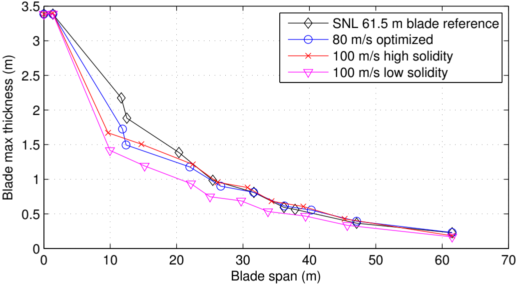


Pareto fronts expressed in terms of approximate system cost

Selected Designs







Structural Optimization

Structural optimization goals included

- **Panel sizing.** Determine the thickness of aft panels, especially near maximum chord where panel span is greatest. The thickness of these panels determines their resistance to buckling.
- **Spar cap sizing.** Determine both the width (constant width) and spanwise layer schedule for the spar cap. The spar cap design affects the overall blade flapwise stiffness and flapwise frequency.
- **Trailing edge reinforcement sizing.** The amount of trailing edge reinforcing material is used to affect the edge stiffness and frequency of the blade.
- **Root buildup.** Constant throughout the study.

Structural Optimization Method

A simple genetic algorithm was used to manage the structural optimization process. The optimization goal was to minimize the penalized blade mass, F_{struc}.

$$F_{struc}(x) = M(x) * P_{\delta} * P_{buckle} * P_{fatigue} * P_{flap} * P_{edge/flap} \quad (5)$$

Penalties P are applied to the blade mass M for exceeding:

- tip deflection criteria, P_{δ}
- buckling criteria, P_{buckle}
- 20 year fatigue damage, $P_{fatigue}$
- flap frequency criteria, P_{flap}
- edge-flap frequency spacing criteria, $P_{edge/flap}$

Design variables, x, included

- (2 variables) foam thicknesses in the aft panels
- (2 variables) determine spar cap thickness distribution
- (1 variable) spar cap width
- (1 variable) determine distribution of trailing edge reinforcement

Rotor Geometry for Maximum Power

The Blade Geometry Parameter (BGP) is an easy way to understand tradeoffs between important aerodynamic parameters at each spanwise blade station:

$$BGP = \sigma_r \lambda C_l \tag{6}$$

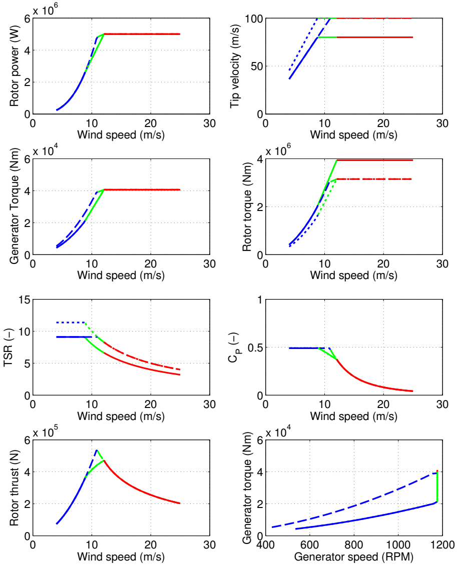
σ_r, rotor solidity (i.e. chord)
λ, tip speed ratio
C_l, local lift coefficient

BGP basically remains constant for a given induction design objective, e.g. maximum efficiency rotor

λ is Tied to Controls Requirements

Illustration of turbine control regions showing three different rotor design approaches:

- solid–low speed, high solidity, low TSR;
- dotted–high speed, low solidity, high TSR;
- dashed–high speed, high solidity, low TSR



Ideal high speed rotor design

Explanation of an ideal scenario for aerodynamic design of a high tip speed rotor is helpful to frame results of this work.

- From a purely aerodynamic perspective, increase in tip speed from 80 m/s to 100 m/s causes increase in rotor TSR of 100/80 = 25%.
- Using this approach, aerodynamic rotor loads do not change, with the exception of the 20% decrease in rotor torque. (see previous slide)
- No change to optimal airfoil design lift coefficients.
- Remember BGP is constant, $BGP = \sigma_r \lambda C_l$
- Therefore, rotor solidity decreases from 4.53 to $4.53/1.25 = 3.624$.
- BUT, so does blade thickness...

What really happens

Structures are adversely affected by the low solidity of an ideal high speed rotor design.

- The decrease in solidity does lead to lighter weight blade skins. But,
- As the ideal rotor solidity and blade thickness decrease with increased rotor speed, the blades' spar caps become disproportionately heavy because their design is driven by blade stiffness.
- The overall blade weight increases because of the larger spar caps.
- There are options:
  - Two-bladed rotors–They come with their own issues.
  - Utilize an airfoil family exhibiting lower design lift coefficients (L/D will suffer).

Summary of rotor designs

	Design 80	Design 100 low solidity	Design 100 high solidity
TSR, λ	8.9	9.9	9.1
Rotor $C_{p,max}$	0.499	0.503	0.493
Rotor C_T	0.743	0.761	0.720
Rotor solidity (%)	4.53	3.76	4.60
Max characteristic rotor thrust (kN)	933 DLC1.3, ETM	1,059 DLC1.3, ETM	1,148 DLC1.3, ETM
Min blade fatigue life (yrs)	17,788 Spar cap	111,682 T.E. reinf.	4,371 Spar cap
Blade mass (kg)	16,097	17,590	16,423

Surprising outcomes:

- Low aerodynamic lift coefficients, C_l
- High blade weight (and cost)
- Increased rotor thrust

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System Results Summary

Changes in system metrics as compared to the optimized 80 m/s rotor system[2].

	Capital cost	AEP	COE
100 m/s high solidity	–2.7%	–4.0%	+2.1%
100 m/s low solidity	–1.8%	+0.3%	–1.5%

Surprise–The heavier blade wins!! *

*This really needs to be repeated with appropriate controls design, though

[2] "Effect of Tip-Speed Constraints on the Optimized Design of a Wind Turbine," NREL/TP-5000-61726

Scope Constraints and Future Work I

Each of the following was out of scope for the first investigation, but are definitely important areas for further work:

- **Rotor size.** Tip speed increases on commercial turbines can be driven by the need for larger swept area when only minimal changes to the balance of turbine are allowed.
- **Turbine wind speed class.** The Turbine class for these designs is IEC I-B. Investigations at lower turbine classes could exhibit different results.
- **Blade materials.** Comparison studies on the use of carbon fiber or glass fiber in the construction of the blades was not included in this work.
- **Innovative airfoils.** Innovative airfoils, e.g. flatback airfoils, were not included as design options in this work.

Scope Constraints and Future Work II

- **Aeroelastic tailoring.** Aeroelastic tailoring, i.e. bend-twist coupling, is a rotor design feature that enables larger swept area with minimal cost to the system in terms of increased rotor loads.
- **Two-bladed rotor.** Individual blade thickness, and therefore structural efficiency, is higher for a two-bladed rotor than a three-bladed rotor with equal solidity.
- **Controls.** The investigation only includes tuning of the Region 2 control constant. Implementation of tuned constants for Region 2.5 and Region 3 are more complicated and were not automated in the optimization framework used for this investigation.
- **Low-load rotors.** Max rotor C_P is not our friend anymore. The concept of low load rotors is becoming almost standard.

Final Thoughts

- Rotor optimization should be performed directly within a system framework.
- When this is not possible, rotor optimization shall be done only with guidance from well-formed system requirements, e.g. interface loads
- The systems engineering tool shall be used to develop the system requirements.
- The role of researchers is to develop disruptive technology to achieve objectives while meeting system requirements.

Questions?