Proceedings of the International Modal Analysis Conference,
January 28-31, 2019, Orlando, FL, US, Paper #5703.

# Dynamics of Extreme-scale Wind Turbines

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**ABSTRACT**
A consistent trend over the years in wind energy technology has been growth in the size of the rotor with associated reduced cost of electricity. Today, wind turbines are reaching rated power of 10 MW with blades of length over 90 meters. The structural design of these immense rotating structures involves satisfying design criteria associated with (1) strength, (2) stiffness and deflection, (3) fatigue life, (4) structural stability, and (5) stable dynamics. The design of the rotor is critical to satisfy all of these design requirements as the rotor captures all of the energy of the wind turbine and transfers all of the loads to the drivetrain and tower support structure. The dynamics of the wind turbine are of particular importance to ensure stability in operation and to mitigate or rather to manage the fatigue loads. For extreme-scale wind turbines (100 meter blades length and beyond) the dynamics are particularly interesting as blades and towers grow longer and more flexible. The dynamics of extreme-scale wind turbines is the focus of this paper including results of recent designs studies and trends in rotor dynamics and loads for extreme-scale machines.

**Keywords:** Wind energy, wind turbine blades, blade design, extreme-scale turbines, dynamics, resonance, flutter

## INTRODUCTION

Today, wind turbines are reaching rated power of 10 MW with blades of length over 90 meters, and the intention is to go even larger. A major challenge to further upscaling lies in the structural design. The structural design of these immense rotating structures involves satisfying design criteria associated with (1) maximum stresses/strains under ultimate loads, (2) limiting blade deflection to avoid blade tower strike, (3) ensuring fatigue life with a design life of 20-25 years, (4) structural stability of blade shell panels to prevent localized buckling, and (5) stable dynamics to avoid resonant conditions and aero-elastic instabilities including flutter. The design of the rotor is critical to satisfy all of these design requirements as the rotor captures all of the energy of the wind turbine and transfers all of the loads to the drivetrain and tower support structure. The dynamics of the wind turbine are of particular importance to ensure stability in operation and to mitigate or rather to manage the fatigue loads.

The dynamics of extreme-scale wind turbines is the focus of this paper including results of recent designs studies by the authors. Trends in rotor dynamics and loads for these designs with blades of length 100 meters to over 140 meters are examined. The study includes results for two rotor configurations with both rated at 13.2 MW: (1) The first is a 3-bladed upwind wind turbine, representing large-scale but conventional wind turbine technology and (2) the second is a 2-bladed downwind wind turbine, which is a new technology being considered for large-scale machines. The basis for the 3-bladed upwind configuration is the Sandia 100-meter blade design series (denoted as SNL100-XX series) and documented in References 1, 2, 3, and 4. The novel 2-bladed downwind configuration is based on the SUMR (Segmented Ultralight Morphing Rotor) concept [5]. As illustrated in Figure 1, the SUMR project has an ultimate goal to achieve the design of an extreme-scale rotor with power of 50 MW and blade lengths exceeding 200 meters, which is significantly larger than today's largest wind turbines; although results of an initial 13.2 MW design study for SUMR is presented here.

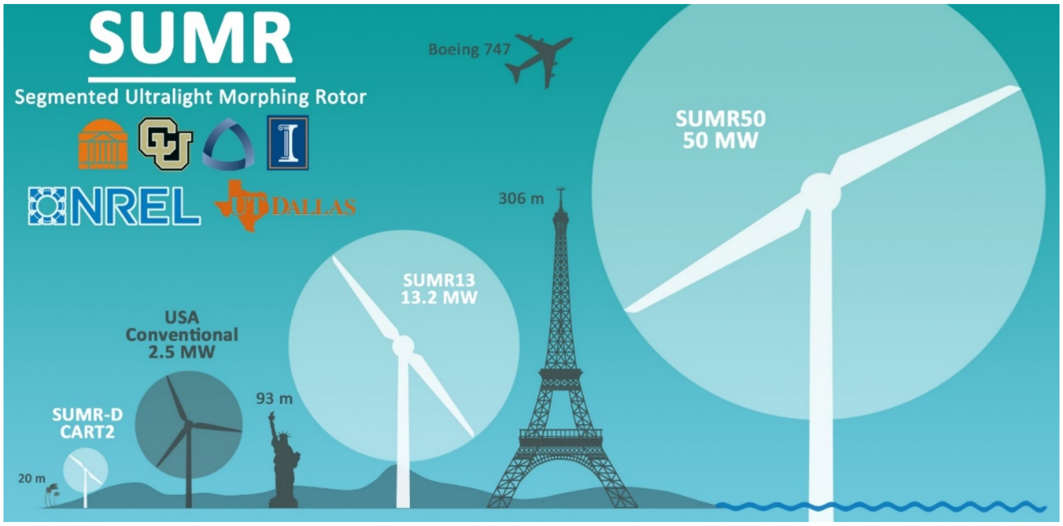


Figure 1: SUMR – Segmented Ultralight Morphing Rotor Concept for Extreme-scale Wind Turbines

In addition to comparing these different 13.2 MW rotor configurations (3-bladed upwind versus 2-bladed downwind), we will examine design trade-offs and trends in blade modal frequencies and flutter instability predictions. These studies are intended to shed light on the design of extreme-scale wind turbines with a focus on the dynamics of these extreme-scale rotors of the future and to demonstrate how these dynamics requirements affect the overall design cycle including checks on strength, deflection, buckling, and fatigue life.

**AUTO NUMAD: A TOOL FOR BLADE DESIGN AND ROTOR ANALYSIS**

AutoNuMAD is a wind turbine blade design tool developed at UT Dallas based on the NuMAD framework by Sandia National Labs [6]. This tool simplifies the process of wind turbine blade design by allowing the user to define design variables and to manage all of the detailed and complicated blade design information including airfoil geometry, varying chord and twist, and detailed composite material layups. Auto NuMAD is a pre-processor for further blade and rotor analysis. Auto NuMAD offers built-in features to perform analyses including a bill of materials, manufacturing cost analysis, modal analysis, Campbell diagrams, flutter prediction, and to output models for analysis in CFD or finite element programs. Figure 2 shows how AutoNuMAD covers all the aspects of blade design and optimization under a unified framework – all features that are essential for the design of blades.

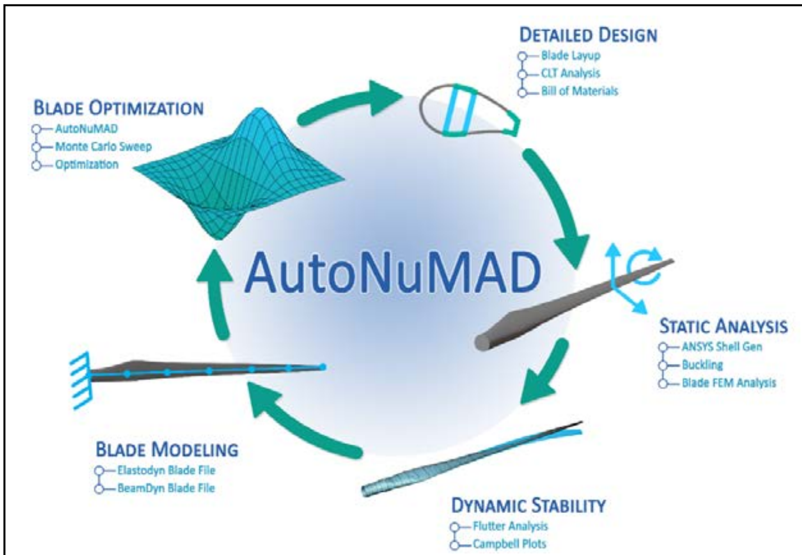


Figure 2: Auto NuMAD: A Design and Analysis Tool for Wind Turbine Blades

**DESCRIPTION OF THE EXTREME-SCALE BLADE DESIGNS**

As noted above, extreme-scale blade models are studied for both a 3-bladed upwind configuration and a novel 2-bladed downwind configuration, both designed for rated power of 13.2 MW.

3-bladed upwind blades include those of the SNL100-XX blade series including SNL100-00 13.2MW [1], SNL100-01 13.2MW [2], SNL100-02 13.2MW [3] and SNL100-03 13.2MW [4]. In addition, the NREL 5MW offshore wind turbine [7] is included for comparison with large utility-scale offshore wind turbines of today. The SNL100-00 blade (for a 13.2MW turbine) is an all-glass 100-meter blade developed at Sandia National Laboratories, this blade was designed to be a baseline for large wind turbine blade design studies. The SNL100-01 blade was designed based on the SNL100-00 baseline, but with a carbon spar cap. The SNL100-02 blade further reduced the weight of the SNL100-01 blade, attributed to the use of advanced core materials in its design. The SNL100-03 blade, the fourth and final design in the series, involved a significant change in geometry and materials. In this design, flatback airfoils were incorporated instead of sharp trailing edge airfoils and a completely new aerodynamic design was developed. From SNL100-00 to SNL100-03, this resulted in a 56% weight reduction for the entire SNL 100-meter series. In more recent work [8], Griffith and Chetan re-designed the SNL100-03 blade to improve the blade flutter performance, which resulted in a new design (UTD100-04). A summary of the properties of these blades are presented in Table 1.

Table 1 also includes properties for a series of blades designs based on the novel 2-bladed downwind SUMR rotor configuration. These blades range in length from 104 meters for SUMR13A, to 122 meters for SUMR13B, and finally 143 meters for SUMR13C. For the purpose of this study, these detailed designs allows us to examine the trends in dynamics for the SUMR13 series and compare with the SNL100-XX series. The planform for the SUMR13C blade is provided in Figure 3.

**Table 1.** Geometry and Operating Specification of the Blade Models Examined in this Study.

| Blade | Length (m) | Maximum Chord (m) | Mass (kg) | Rated Power (MW) | Rated Speed (rpm) |
|---|---|---|---|---|---|
| NREL 5MW [7] | 61.50 | 4.60 | 17,740 | 5.00 | 12.10 |
| SNL100-00 [1] | 100.00 | 7.628 | 114,172 | 13.2 | 7.44 |
| SNL100-01 [2] | 100.00 | 7.628 | 73,995 | 13.2 | 7.44 |
| SNL100-02 [3] | 100.00 | 7.628 | 59,047 | 13.2 | 7.44 |
| SNL100-03 [4] | 100.00 | 5.226 | 49,519 | 13.2 | 7.44 |
| UTD100-04 [8] | 100.00 | 5.226 | 49,126 | 13.2 | 7.44 |
| SUMR13A (carbon) [5] | 104.35 | 7.512 | 54,300 | 13.2 | 9.55 |
| SUMR13A (glass) [5] | 104.35 | 7.512 | 80,800 | 13.2 | 9.55 |
| SUMR13B (carbon) [5] | 122.87 | 6.791 | 101,800 | 13.2 | 7.99 |
| SUMR13C (carbon) [5] | 143.45 | 9.286 | 111,400 | 13.2 | 7.00 |

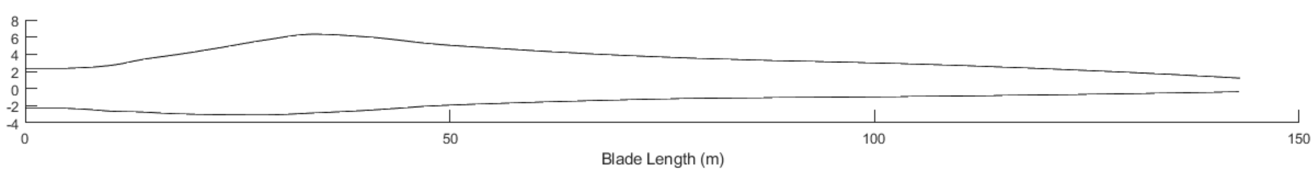


Figure 3: Planform for the SUMR13C Wind Turbine Blade

It is important to emphasize that each of the blade designs listed in Table 1 are detailed blade designs satisfying design requirements (as shown in Figure 4) for (1) strength, (2) deflection, (3) fatigue, (4) buckling, and (5) dynamics. International design standards are utilized along with application of a wide range of design load cases to ensure acceptability of the designs with respect to the requirements of the design standards for commercial blades.

Table 1 shows design specifications for the structural performance of all blades in this study following the blade design standards based optimization steps described in Figure 4. A few trends can be noted from the table. For the SNL100-XX series, the significant mass reduction (of over 56%) from the initial baseline SNL100-00 to final UTD100-04 design can be noted. An additional 25% mass reduction of the rotor was achieved for the SUMR concept in comparing the mass of the 2-bladed SUMR13A rotor with the mass of the 3-bladed SNL100-03 rotor.

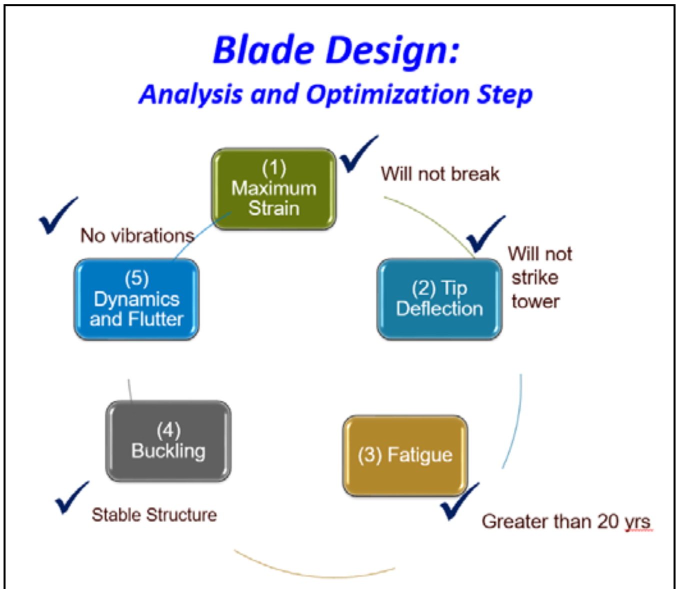


Figure 4: Blade Structural Design Loops

Table 2 summarizes the key dynamics information for the blade designs including blade frequencies (the 1st flap-wise and 1st edge-wise blade frequencies) and the predicted flutter speeds (rpm) for each blade. Note the flap-wise direction is normal to the chord line while the edge-wise direction is along the chord line (typically defined at the blade tip airfoil). A few trends can be noted from Table 2:

1. The effect of carbon is clear in not only reducing the blade mass but increasing the blade frequencies (e.g. SNL100-00 to SNL100-01 and SUMR13A (carbon) versus SUMR13A (glass)).
2. The weight reduction in SNL100-01 versus SNL100-00 enabled a reduction in the trailing edge reinforcement of SNL100-01. As a result, the edge-wise frequency of SNL100-01 was reduced significantly (although the flap-wise frequency increased significantly).
3. The most lightweight of the SNL100-XX series (the SNL100-03 and UTD100-04 designs) utilized new flatback airfoils and a more slender aerodynamic design, which resulted in further reduction in both flap-wise and edge-wise frequency.
4. For the SUMR13 series, the effect of longer blade length in reducing blade frequencies is evident, as would be expected by conventional upscaling of blade length.
5. It's interesting; however, that the flap-wise and edge-wise frequencies for SUMR13A (carbon) increase versus the similar sized UTD100-04 design. This is due to geometry as both designs use the same materials.
6. Lastly, the flutter speeds are analyzed. Flutter speed (rpm) is predicted by Auto NuMAD based on the methods detailed in [8]. A flutter ratio is calculated by dividing the flutter speed by the rated (maximum) rpm of the rotor, which is provided in Table 1. A flutter ratio greater than 1.0 (1.20 in practice) is required for flutter-free operation. For the SNL100-XX series (as reported in [8]), it is clear the trend toward lower flutter ratio (lower per-rev flutter speed) with mass optimization of the rotor.
7. For the SUMR13 series, flutter was identified as a critical design issue and was addressed directly as a design objective in those designs. Thus, no clear trends can be gained in comparing the series (other than to indicate that flutter mitigation is possible if directly considered in the design process). Structural design considerations to mitigate flutter are addressed in Reference [8].

**Table 2.** Summary of Key Blade Dynamics Information for Blade Models Used in this Study.

| Parameter | SNL100-00 (glass) | SNL100-01 (carbon) | SNL100-02 (carbon) | SNL100-03 (carbon) | UTD100-04 (carbon) | SUMR13A (carbon) | SUMR13A (glass) | SUMR13B (carbon) | SUMR13C (carbon) |
|---|---|---|---|---|---|---|---|---|---|
| Airfoil Type | DU-series (sharp TE) | DU-series (sharp TE) | DU-series (sharp TE) | FB-series (flatback) | FB-series (flatback) | F1-Series (flatback) | F1-Series (flatback) | F1-Series (flatback) | F1-Series (flatback) |
| Blade Length (m) | 100 | 100 | 100 | 100 | 100 | 104.3 | 104.3 | 122.8 | 143.4 |
| Blade Mass (kg) | 114,172 | 73,995 | 59,047 | 49,519 | 49,126 | 54,300 | 80,800 | 101,757 | 111,453 |
| 1st flap-wise frequency (Hz) | 0.425 | 0.495 | 0.553 | 0.509 | 0.493 | 0.565 | 0.409 | 0.387 | 0.339 |
| 1st edge-wise frequency (Hz) | 0.729 | 0.677 | 0.687 | 0.612 | 0.604 | 0.627 | 0.460 | 0.459 | 0.470 |
| Flutter Speed (rpm) | 14.44 | 12.81 | 11.64 | 9.84 | 10.86 | 10.3 | 12.951 | 8.37 | 8.19 |
| Flutter ratio (-) | 1.94 | 1.72 | 1.56 | 1.32 | 1.46 | 1.08 | 1.36 | 1.05 | 1.17 |

## CONCLUSION

Wind turbines are literally reaching new heights with rated power of 10 MW and blades of length over 90 meters. In order to achieve further cost reduction, even larger rotors are sought. Structural design limits are a major challenge, and one solution is to consider new rotor technologies (for example, 2-bladed downwind rotors as was considered here). The structural design of these immense rotating structures involves satisfying competing design factors associated with (1) maximum stresses/strains under ultimate loads, (2) limiting blade deflection to avoid blade tower strike, (3) ensuring fatigue life with a design life of 20-25 years, (4) structural stability of blade shell panels to prevent localized buckling, and (5) stable dynamics to avoid resonant conditions and aero-elastic instabilities including flutter.

The focus of the paper was on the fifth and final factor, the blade dynamics for extreme-scale wind turbines. This involves an examination of the blade modal frequencies and aero-elastic stability (flutter speeds) of the rotor. The goal is to ensure stable turbine dynamics with both resonance-free operation and flutter-free operation. Trends in both modal frequencies and flutter speeds were examined for two series of blades design for 13.2 MW wind turbines: one for 3-bladed upwind machines and another series of blades for 2-bladed downwind machines.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from the US Department of Energy's Advanced Research Project Agency Energy (ARPA-E) and the entire SUMR project research team at University of Virginia, University of Illinois, University of Colorado at Boulder, Colorado School of Mines, and National Renewable Energy Laboratory (NREL).

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