Leading Edge Microspoilers for Load Dumping in Wind Turbine Rotors

B Mertz[1], P Bortolotti[2], N J Abbas[2,3], N Johnson[2], J Paquette[4], W Jordan[1]

[1]Rose-Hulman Institute of Technology, Terre Haute, IN 47803, USA.
[2]National Renewable Energy Laboratory, Golden, CO 80401, USA.
[3]University of Colorado Boulder, Boulder, CO 80309, USA.
[4]Sandia National Laboratories, Albuquerque, NM 87185, USA.

E-mail: `mertzb@rose-hulman.edu`

Abstract. As rotor designs have grown in size and flexibility, new design challenges have arisen that could benefit from novel control strategies. Leading edge microspoilers (LEMS) have been shown to effectively reduce forces on airfoils by inducing stall at lower angles of attack. This paper investigates how LEMS can be used to reduce blade loading on large, flexible, downwind rotors during design-limiting design load cases. During shutdown in turbulent flows near cut-out speed, LEMS could reduce the tip deflection spikes toward the tower by over 50% and keep flapwise root bending moments below normal operating conditions, thus eliminating these as design-driving load cases. In power producing load cases, deploying LEMS for a short period of time during a load spike can be effective to reduce toward-tower tip deflections without significantly impacting power produced, assuming these load spikes can be identified by a controller. Leveraging this technology could allow for lower specific power machines to be designed.

1. Introduction

Industry trends toward low specific power wind turbines have resulted in the development of large, highly flexible rotor designs. While this trend has led to reductions in cost of energy by leveraging energy production at lower wind speeds, there are often increased loads and out-of-plane tip deflections that become design drivers at high wind speeds [1]. This work presents numerical simulations that demonstrate how leading edge microspoilers (LEMS) can be effective at reducing loads on large, highly flexible, downwind rotors during extreme load cases. This is part of a larger research effort funded by the U.S. Department of Energy called the Big Adaptive Rotor (BAR) project, which seeks to develop technologies that support the industry trend toward lower specific power machines. Distributed aerodynamic control (DAC) is one such technology. There have been many studies that have addressed challenges associated with DAC, but most have focused on the use of trailing edge devices and have targeted fatigue loads [2,3]. Trailing edge flaps have already been studied on upwind turbine configurations of the BAR rotor to reduce fatigue loads [4]. A review article by Johnson et al. [5] describes and classifies a number of different active and passive flow control devices found in literature, including LEMS, and discusses how they might be used in wind turbine designs.

LEMS are small (on the order of a few millimeters in height), vertical fences that protrude perpendicular from the low-pressure side of an airfoil surface near the leading edge (usually in the first 10% of chord length) that are meant to induce stall at much lower angles of attack. Lewis, et al. [6] experimentally showed that LEMS can reduce the lift-to-drag ratio of an airfoil by up to a factor of 22 (from peak lift-to-drag ratios of 100 to 4.5). An important limitation of traditional pitch control for large rotors is that the large mass of the blades limits pitch rates to between 1-2 deg/s and so during extreme shutdown cases it may be difficult to rapidly unload the blades. The large control authority, simplicity, and fast deployment of LEMS make them appealing as an active flow control device, but since they can only reduce blade loading, the appropriate deployment scenarios must be targeted to produce an overall net benefit on the rotor design.

As a part of the BAR project, 100 m long, extremely flexible, rail-transportable blades were designed such that they could bend during transit. Bortolotti et al. [7] evaluated both upwind and downwind configurations of this BAR rail-transportable rotor and found that in the downwind configuration, 3 of the 5 largest out-of-plane tip deflections toward the tower occurred in design load case (DLC) 5.1 cases (turbulent wind with shutdown) near cut-out speeds. As downwind rotors experience high wind speeds and pitch angles, the blades can produce negative lift, resulting in tip accelerations toward the tower and are the situations to consider when evaluating minimum tower clearance constraints [8]. This "snap back" phenomena is observed in these DLC 5.1 cases on the BAR downwind rotor. Since this load case involves a load-shedding event, this is a promising situation to evaluate the benefits of deploying LEMS.

2. Objectives

This paper seeks to characterize the use of LEMS to reduce tip deflections toward the tower and blade loads during an emergency shutdown maneuver and during power production load cases where there are distinct spikes in blade loading. The BAR, downwind, highly flexible, carbon spar rotor was used as a test case. A parameter study of spanwise size and placement of the LEMS was conducted and each case was evaluated for effectiveness in reducing both the amount of out-of-plane tip deflections toward the tower and the flapwise root bending moment loads that occurred during the shutdown procedure. During power production, specific load spikes were targeted and the ability of the LEMS to reduce the spike while maintaining power production was evaluated.

3. Methodology

The Wind Energy with Integrated Servo-control (WEIS) framework is an open-source, Python-based framework that integrates into a single environment the hydro-aero-servo-elastic solver OpenFAST, the algorithmically tuned dynamic Reference Open-Source Controller (ROSCO) [9], the turbulent wind solver TurbSim, and routines to run the design optimization of the whole wind turbine system. In these simulations, the Minnema/Pierce variant [10, 11] of the unsteady aerodynamics model was used, but was automatically turned off when local angles of attack exceeded 45 deg. Within this project, WEIS was modified to add the capability to generate aerodynamic lift and drag polars for airfoil sections with DAC devices using a low-fidelity modeling approach [12]. Polar modification mapping parameters were found using data on LEMS from Lewis et al. [6]. The LEMS were programmed to fully deploy as soon as a shutdown was triggered. The Euler-Bernoulli beam solver, ElastoDyn, was used to model the elastic response of the blades.

The low-fidelity modeling approach assumes that the effect of the active flow control device does not depend upon airfoil geometry and hence the modification mapping parameters can be used to modify any arbitrary baseline airfoil lift and drag polars to account for the effects of the flow control device. Since there are no data from literature related to the effects of LEMS on the airfoil geometries that are used in the test case rotor design used for this paper, a

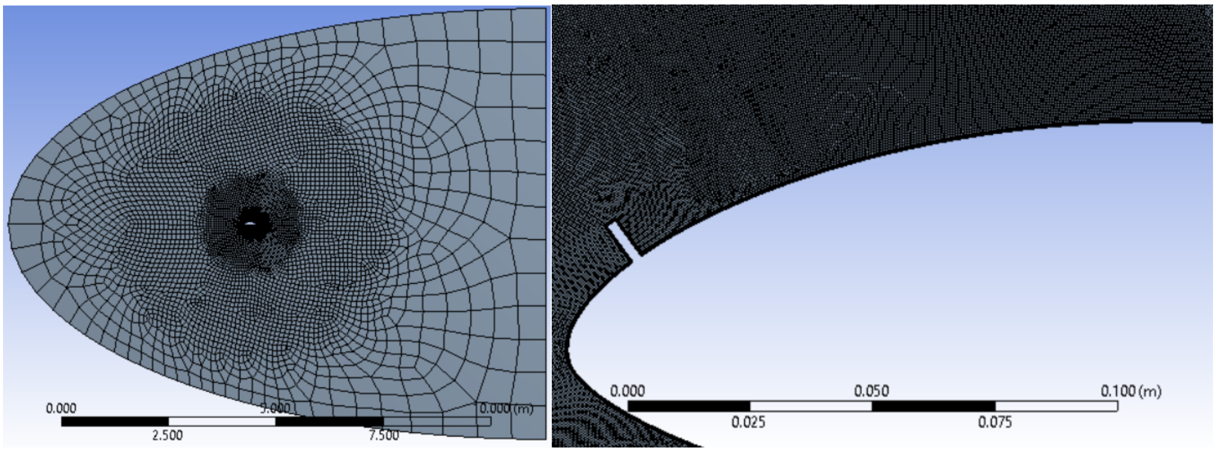

Figure 1. Mesh used for CFD simulation of FFA-W3-211 airfoil with LEMS ($\approx 225,000$ nodes with clustering around the leading edge)

Reynolds-averaged Navier-Stokes computational fluid dynamics (CFD) simulation using Ansys Fluent was conducted for the FFA-W3-211, which is used at the 73.6% span location in the baseline rotor design. A validation CFD simulation was performed on the NASA LS (1)-0417 MOD airfoil geometry used by Lewis et al. [6] to validate the meshes and turbulence models used in the simulation of the FFA-W3-211 airfoil. The $k-\omega$ shear stress transport (SST) model with approximately 225,000 nodes with clustering additional nodes around the leading edge was able to accurately capture the effects of the LEMS. The meshes used for the FFA-W3-211 simulation can are shown in Figure 1.

The low-fidelity modeling approach was then applied to the polars used in the baseline rotor design to mimic the effects of the LEMS. The comparison between the low-fidelity model results and the CFD results are shown in Figure 2. The low-fidelity model captures the important effects of the LEMS device without changing the polar modification parameters from the original tuning using the Lewis et al. experimental data. The agreement was deemed to be sufficient to reasonably use the low-fidelity model to approximate the behavior of the LEMS devices for this exploratory study. However, more accurate polars for the LEMS deployed cases would be needed for a more detailed rotor design with LEMS.

A total of 15 different LEMS size/placement configurations were tested with spanwise sizes up to 45% and as small as 5%, as shown in Table 1. Additional cases were simulated for LEMS of different sizes that were placed more inboard, but were not included in this paper because, as expected, the further away from the hub the LEMS were placed, the greater their impact on tip displacement and root bending moment loads. With this in mind, the end of the LEMS was fixed at the 95% span location and the spanwise extents were varied in order to isolate the size effects. Each configuration was tested at four different average wind speeds (17 m/s, 19 m/s, 21 m/s, and 23 m/s) and six different turbulence seeds (a total of 24 different wind cases). The cut-out speed of this particular downwind rotor was limited to 19 m/s due to tower clearance concerns. The highest two wind speeds in this study thus represent extreme cases that are outside of the design envelope. However, these simulations demonstrate how LEMS could be used to mitigate tower clearance concerns, allowing designers to explore a larger design space and reinstate a more standard cut-out speed. The increased cut-out speed could increase annual energy production. A baseline case was also run for each configuration and wind case in which the low-fidelity model was used to create the aerodynamic polars, but the LEMS was not

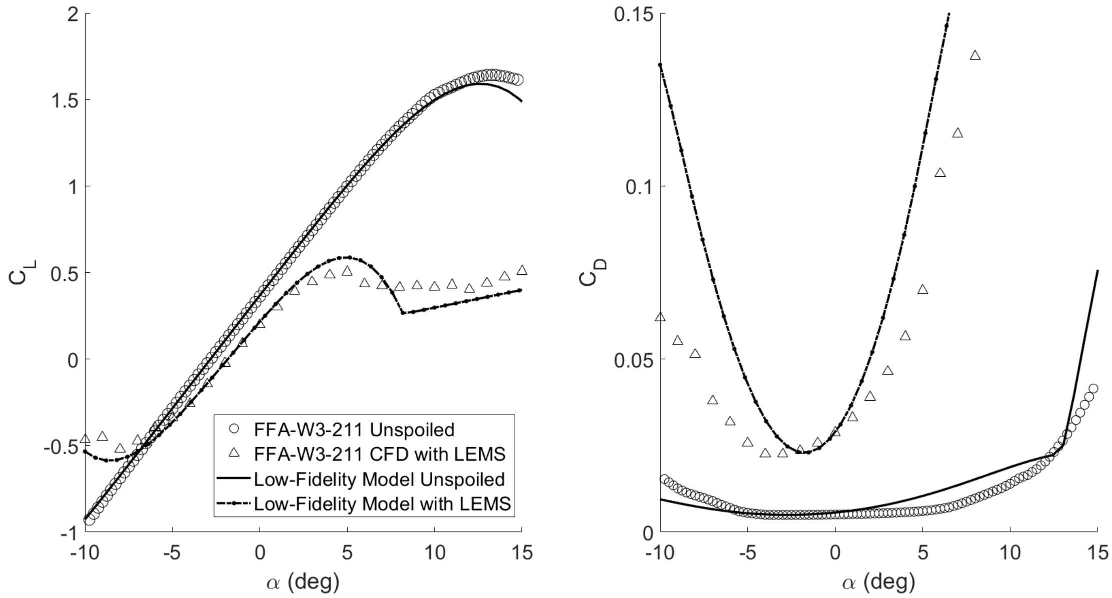

Figure 2. Lift and drag polar comparison between low-fidelity modeling approach and CFD results for FFA-W3-211 airfoil

Table 1. LEMS size and placement configurations test matrix

LEMS Start (% Span)	LEMS End (% Span)	LEMS Extent (% Span)	LEMS Start (% Span)	LEMS End (% Span)	LEMS Extent (% Span)
50	95	45	80	95	15
60	95	35	90	95	5
70	95	25			

deployed so that the effects of the LEMS could be isolated. All of the results are given in terms of differences from the baseline case.

Time series of tip deflection and flapwise root bending moments were analyzed during the shutdown maneuver and the largest loads and tip deflection (toward the tower) values that occurred during that time were recorded for comparison. A representative example of one of these time series for the largest LEMS tested is provided in Figure 3. The simulations were run for 720 s of simulation time and the first 120 s are removed from analysis to avoid transient effects associated with starting the simulation. The shutdown is triggered at the 420 s time mark, and it takes approximately 40 s for the pitching maneuver to complete due to the low maximum pitch rate. Most of the time, the maximum loads/deflections toward the tower occur within the first 10 s of the maneuver. Note that a negative out-of-plane tip deflection is toward the tower in all time series plots.

4. Results and Discussion

The 24 different wind cases were simulated for the baseline downwind rotor and then again for the 5 different LEMS configurations in Table 1 with a simulated emergency shutdown. The percent change in the peak toward-tower tip displacement during shutdown were averaged over all turbulence seeds for each average flow speed and plotted in Figure 4. All of the LEMS sizes tested reduced the toward-tower tip displacements. The smallest changes for all LEMS spoiler

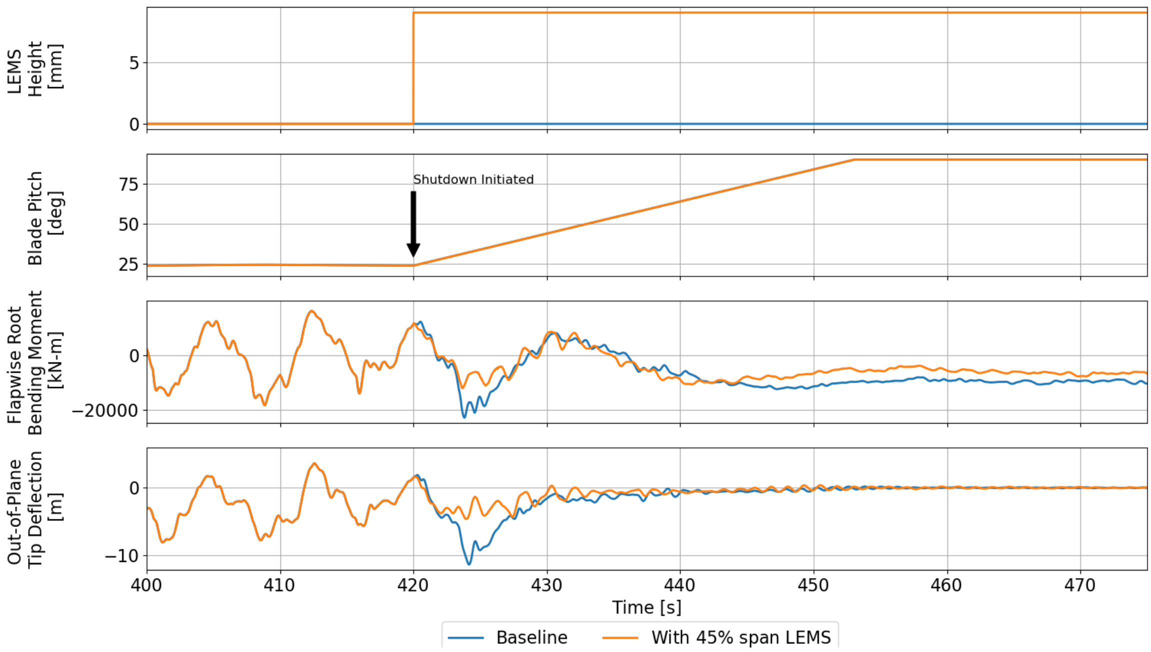

Figure 3. Example time series of LEMS spoiler height, blade pitch angle, flapwise root bending moment and tip deflection with and without 45% span LEMS deployed at shutdown (region of time around shutdown maneuver is being isolated)

sizes occurred at 19 m/s, which is the designed cut-out speed of the rotor. The 45% extent LEMS appears to be less effective than the 35% extent, which was not expected. However, it was observed that the maximum baseline tip deflections in the 45% extent cases were, on average, smaller than in the 35% extent cases and thus made the percentages lower. This is attributed to the slight differences between using the low-fidelity model polars without LEMS deployment and the unmodified polars in the reference turbine design. Both the 35% extent and the 45% extent LEMS simulations brought the flapwise root bending moment loads and tip deflections to comparable levels when deployed, which may indicate that there is not much benefit to including the extra 10% of extent.

To evaluate the LEMS effectiveness more consistently, the turbulence seed case with the largest toward-tower tip deflections during shutdown in the baseline case for each average wind speed were identified. The percent change in the tip deflections for LEMS of different spanwise sizes were plotted in Figure 5 for these worst-case scenarios. The 5% span LEMS were able to reduce the worst-case, maximum, toward-tower tip deflections by 20% whereas the longer spoilers were able to reduce the deflections at the highest wind speeds by over 50%. Using LEMS with a 25% span or larger, the tip deflections during shutdown were below the maximum operating tip deflections. Note that the maximum absolute flapwise root bending moment loads were also reduced by deploying the LEMS (see Figure 3).

The use of LEMS during a shutdown event is both effective at reducing out-of-plane, toward-tower tip deflections and the standard controller already provides a convenient trigger for the LEMS device via the controller's shutdown criteria. The use of LEMS for power-producing design load cases (such as DLC 1.3) is more difficult because the controller would need to target unwanted extreme loads while not significantly reducing power over the majority of the operational time. Bortolotti et al. [7] found that for the downwind rotor used in this study, the remaining load cases that produced design-limiting out-of-plane tip deflections toward the tower were DLC 1.3 cases with average wind speeds at the cut-out speed (19 m/s). However, as shown

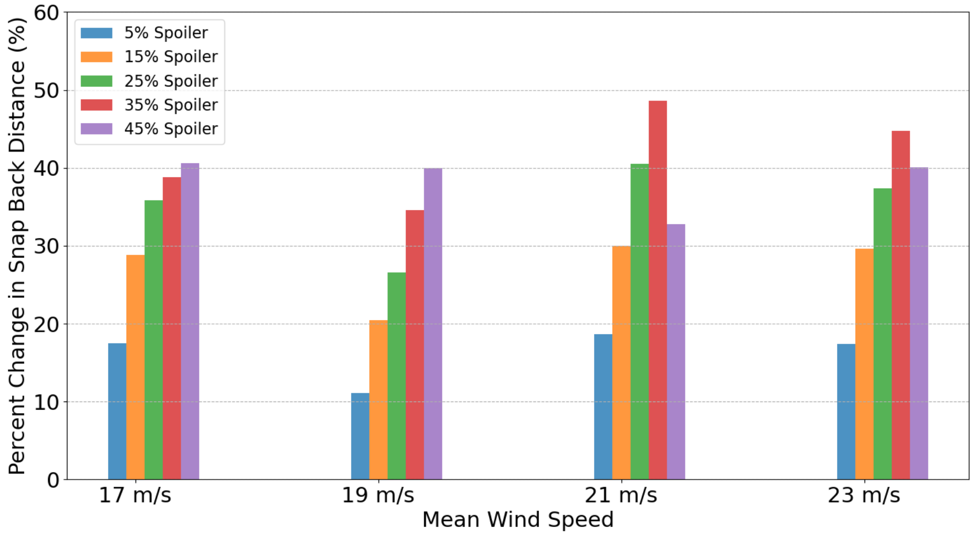

Figure 4. Percent decrease in maximum tip deflection toward-tower during shutdown averaged over all wind cases with different LEMS spanwise lengths

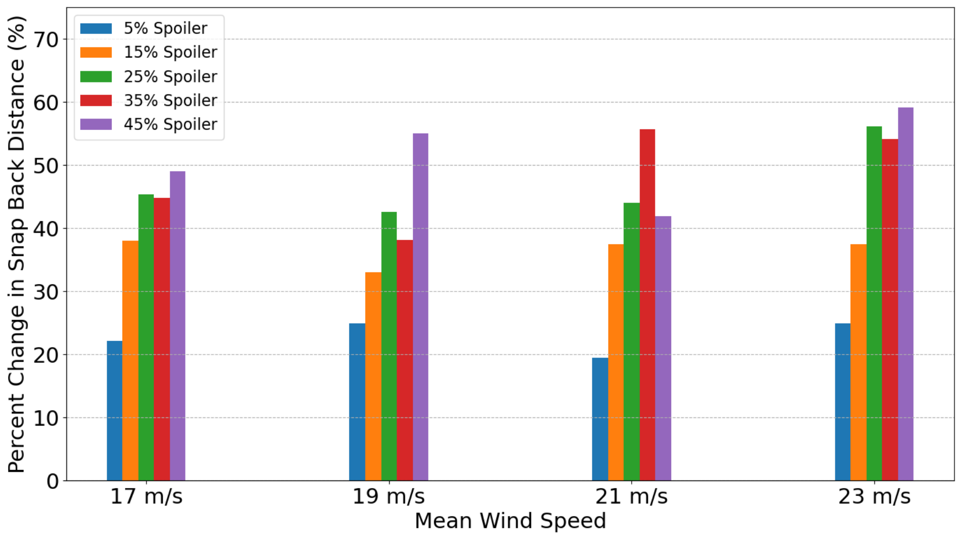

Figure 5. Percent decrease in maximum tip deflection toward-tower during shutdown for worst wind case with different LEMS spanwise lengths

in Figure 6, the maximum toward-tower tip deflections mostly appear as short duration spikes. If those spikes could be targeted and reduced using LEMS, this could address the design-driving nature of these DLCs. Note also that these kinds of toward-tower spikes in blade tip deflection appear in both upwind and downwind configurations. In fact, the top five largest out-of-plane tip deflection DLCs for the upwind version of the rotor being used in this paper are all power-producing load cases (DLC 1.3 and 1.4). Being able to target specific spikes in tip deflection would therefore have relevance for LEMS use in upwind rotors as well.

Since we are only trying to understand the potential impact of the LEMS devices on turbine performance, developing a controller to trigger the deployment is beyond the scope of this paper, but is a relevant area of future work that we wish to explore. For this paper, we attempted

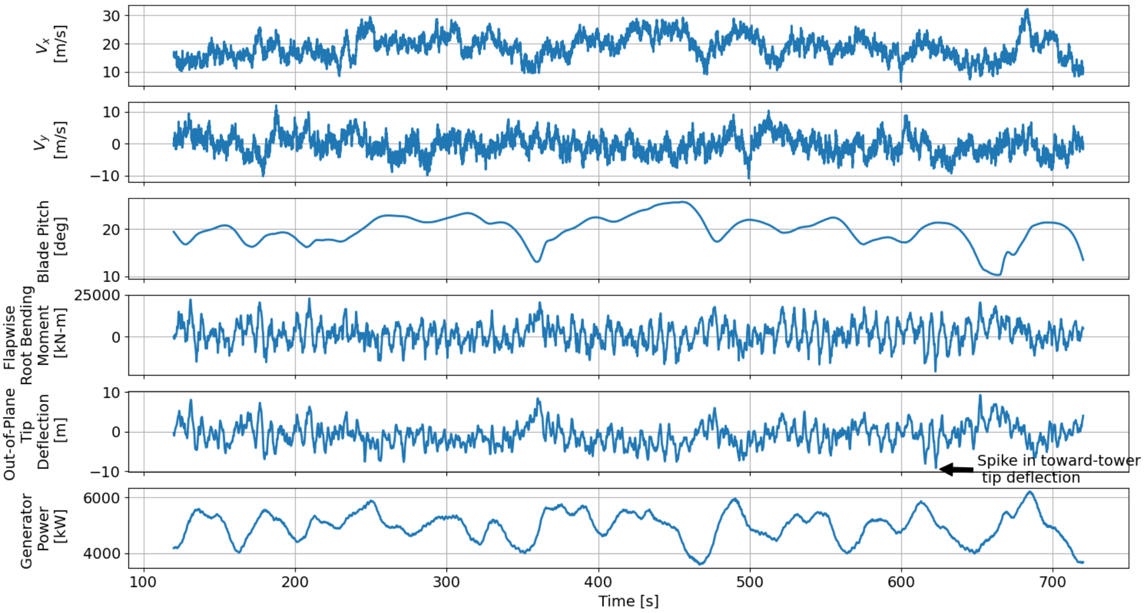

Figure 6. Time series of baseline downwind rotor configuration performance for DLC 1.3 at the cut-out wind speed of 19 m/s. Plotted parameters: x-component of wind speed (V_x), y-component of wind speed (V_y), blade pitch angle, flapwise root bending moment, out-of-plane tip deflection, and output generator power.

to alleviate the largest spike in tip deflection toward the tower by manually triggering a 45% span LEMS at 622 s of simulation time (the time when the tip deflection approaches the largest normal operating values before the peak occurs). The duration of deployment was limited to 1 s, which is approximately the duration of the spike in the baseline simulation. The time series shown in Figure 7 is zoomed in on the time frame around the LEMS deployment so that the impact can be more clearly seen. During the LEMS deployment, the tip deflection decreased from -9.24 m to -6.31 m ($\approx$ 32% reduction) and there was a corresponding decrease in flapwise root bending moment. During deployment, there was a negligible decrease in generator output power. The turbine performance returned back to the baseline performance within 2 s of the LEMS being retracted.

These preliminary results suggest that a LEMS controller could be developed to determine when these spikes are likely to occur and to deploy the LEMS devices briefly to reduce blade loads without a significant reduction in power. Future work will include looking at indicators in standard blade sensor signals that suggest an appropriate time to deploy LEMS devices and to develop a LEMS-specific controller logic accordingly. Care will have to be taken so that these devices are not deployed too often and hence contribute to additional fatigue loading on the blade or cause concerns related to fatigue on any future LEMS deployment system. Again, these results are also promising for future research on effectively using LEMS devices in highly flexible upwind rotor designs. Future work also includes learning ways to leverage LEMS devices' ability to change the design-driving load cases to decrease the levelized cost of energy.

One of the major limitations of this study is the reliance upon the low-fidelity model of the LEMS devices to develop the aerodynamic polars. While the general effects of the devices are captured with this approach, more work needs to be done to develop better aerodynamic polars for when LEMS devices are deployed. Work also needs to be done to determine if there are any transient effects of LEMS deployment that are currently not being modeled. This

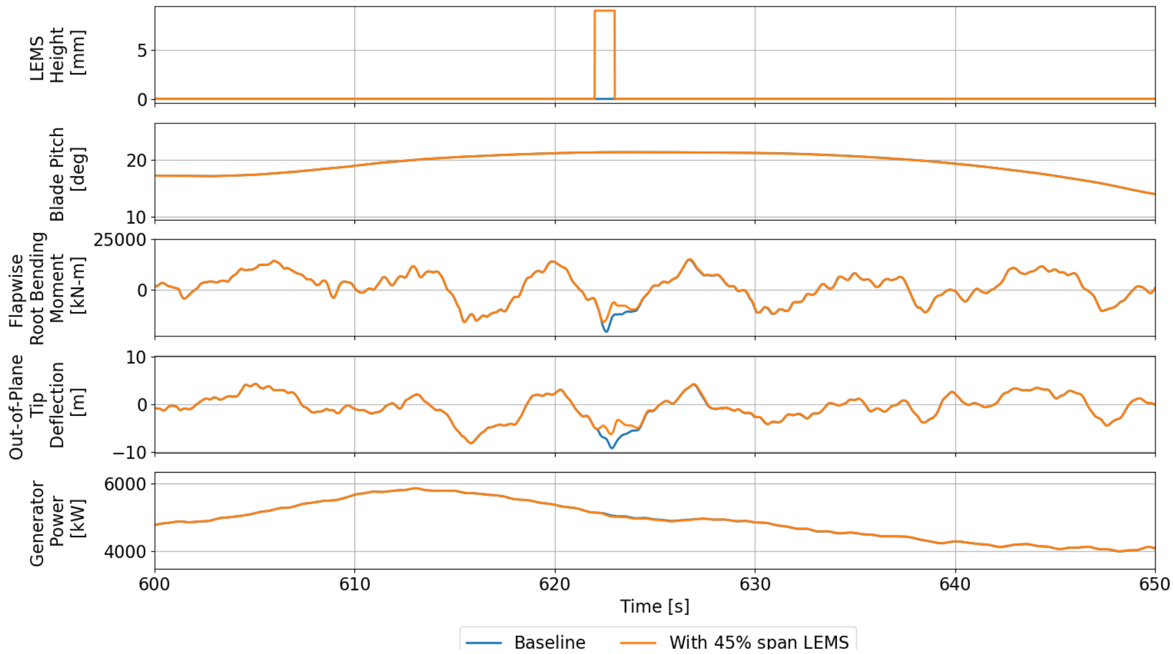

Figure 7. Time series of the baseline downwind rotor configuration performance with and without LEMS for DLC 1.3 at the cut-out wind speed of 19 m/s zoomed in on time of LEMS deployment.

will be particularly important to understand in order to target specific conditions in the power-producing design load cases. Higher-fidelity simulations that use the structural-dynamics module BeamDyn and/or blade-resolved CFD studies would also be beneficial to better understand the impact of such devices on wind turbine performance. Finally, experimental studies of particular LEMS actuator designs would be needed before prototype testing can be conducted on actual wind turbine blades.

5. Summary
A design-limiting emergency shutdown DLC was identified and simulated for large flexible downwind rotors and LEMS were shown to significantly reduce blade loads and deflections during such events. For power-producing design load cases, specific short-duration peaks in blade loading can be reduced if a controller can be developed to identify when to employ the LEMS to target these peaks. This can be leveraged to increase the cut-out speed, reduce cone/tilt angles, or increase the blade length in order to decrease LCOE.

6. Acknowledgements
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