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Wind Turbine Structural Path Stress & Fatigue Reductions Resulting from Active Aerodynamics*

Dale Berg and Brian Resor
Wind Energy Technologies Department
Sandia National Laboratories†
P.O. Box 5800, MS-1124
Albuquerque, NM 87185-1124
USA
deberg@sandia.gov
brresor@sandia.gov

Zach Wright, Chris Halse and Ashley Crowther
Romax Technology Ltd
2845 Wilderness Pl.
1st Floor
Boulder, CO 80301
USA
Zach.Wright@romaxtech.com
Chris.Halse@romaxtech.com
Ashley.Crowther@romaxtech.com

Introduction

In the first decade of the 21st century the wind industry grew at rates consistently above 20% a year in terms of global cumulative installed capacity (MW), according to the Global Wind Energy Council[1], as illustrated in Figure 1. In 2009 the growth was 31% despite the global economic crisis. Accompanying this rapidly expanding market and the attendant growth in machine size are significant issues with the reliability in the drive train, electrical systems, pitch systems and yaw systems. Tavner, et al.[2] present reliability statistics for a European database of wind turbine failures and the analysis of the LWK[3] survey of 643 wind turbines. This information is summarized below in Figures 2 and 3. These statistics show the gearbox, main shaft, pitch and yaw systems all have significant failure rates and, in particular, failures in the drivetrain bring the highest downtime.

These reliability issues threaten the sustained growth of the market; the need for improved reliability and robust designs has brought an industry wide effort to address these issues. Evidence of this effort are found in the development of a new IEC standard 61400-4, *'Wind Turbines - Part 4: Design and Specification of Gearboxes'* (replacing ISO 81400-4:2005), the National Renewable Energy Laboratory Gearbox Reliability Collaborative (NREL GRC)[4] and the establishment of the Sandia National Laboratories Database Continuous Reliability Enhancements for Wind (CREW) Database[5].

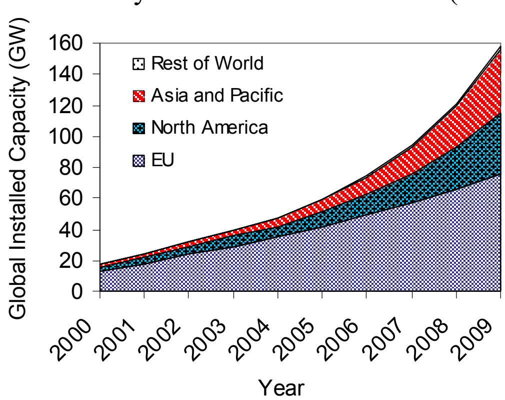

Figure 1. Global Installed Capacity from 2000-2009[1]

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† Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

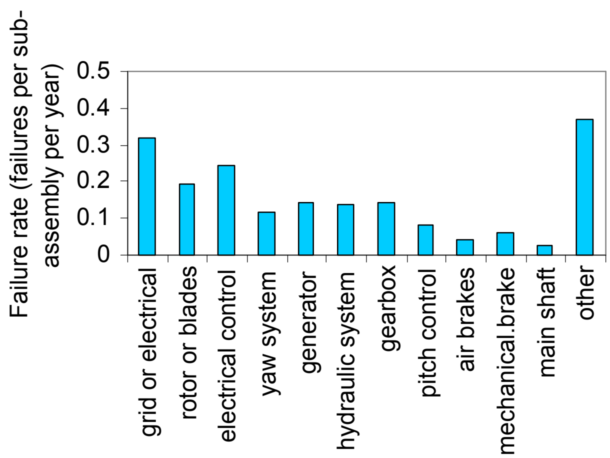


Figure 2. Failure Rate of Wind Turbine Components[2]

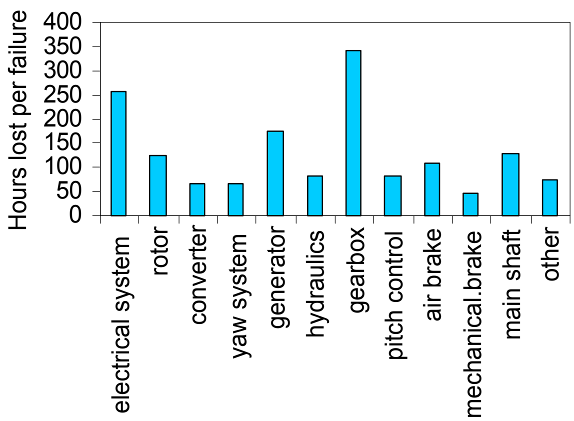


Figure 3. Hours Lost per Failure for Wind Turbine Components[2]

The wind-induced loads on a large rotating wind turbine blade vary quickly in time and space due to the stochastic nature of the wind and the fact that the sizes of coherent structures in the wind (the gusts) are significantly smaller than the length of the blades; the resulting blade oscillating (or fatigue) loads frequently are the design drivers for the turbine blades and some components of the drive train.

According to the DOE "20% Wind Energy by 2030"[6] report, one way to reduce COE "…lies in an active control that senses rotor loads and actively suppresses the loads transferred from the rotor to the rest of the turbine structure. These improvements will allow the rotor to grow larger and capture more energy without changing the balance of the system." In particular, one concept for suppressing the fatigue loads acting on large turbine blades is to implement small, fast response, aerodynamic control devices (with associated sensors and control systems to sense the existing loading and direct appropriate control device action) distributed along each blade to provide feedback load control (often referred to in popular terms as 'smart structures' or 'smart rotor control'). A recent review of this concept, including a discussion of the feasibility of the concept and an inventory of design options for such systems, has been performed by Barlas and van Kuik at Delft University of Technology (TUDelft)[7]. One attractive control device design option is that of utilizing trailing edge flaps or deformable trailing edge geometries; this option is referred to here as Active Aerodynamic Load Control or AALC. This technology is a focus of research at several locations, because of the direct lift control capability of trailing edge devices and recent advances in smart material actuator technology. Researchers at TUDelft[8,9], Risø Danish Technical University National

Laboratory for Sustainable Energy (Risø/DTU)[10-16] and Sandia National Laboratories (SNL)[17-21] have been very active in this area over the past few years. Researchers at SNL have performed extensive simulations of AALC on several turbine configurations and have analyzed the simulation results to estimate the fatigue damage reduction benefits of AALC and the decreases in cost of energy that might result from integrating AALC technology into the tip region of turbine blades.

The subject of nearly all AALC studies to date has been the reduction of blade fatigue loads. However, reducing ultimate and fatigue loads on wind turbine blades may also result in the modification of loads on other turbine components such as rotor hubs, main bearings, gearboxes, main frames, generators and towers, potentially resulting in large reductions in both the initial capital costs and the maintenance costs. These reductions in loads may, in turn, provide a significant decrease in the resultant turbine cost of energy. The Berg et al[21] report, a preliminary study performed in 2010, demonstrated that, as a side effect of controlling the fatigue loads on the rotor of a 1.5MW turbine, AALC also leads to reductions in damaging off-axis oscillatory loading, such as side loads and overturning moment, on a typical turbine gearbox. Those reductions could be expected to lead to reduced gearbox bearing fatigue damage and improved lifetimes. That study suggests that the use of AALC may result in mitigating damage to all drive train components by reducing the off-axis oscillating loads that the main shaft bearings otherwise have to support. This current work expands on that preliminary work by examining the impact of AALC on several major components in the structural load path between rotor blades and turbine tower top.

Overview of NREL GRC Project

The National Wind Technology Center (NWTC) has been running the Gearbox Reliability Collaborative project (GRC) for the Department of Energy. This important project brings together gearbox engineers, manufacturers, owners, expert consultants, academics and other partners from the wind industry in an effort to collectively improve gearbox reliability, through improved understanding of the causes of poor reliability. The ultimate goal of this project is to decrease the costs associated with operations and maintenance of these major drivetrain components.

A key goal of the GRC was to comprehensively instrument two gearboxes for measurements of tooth root strains, bearing temperatures, bearing raceway strains, gearbox motion, carrier motion, torque, speed and other parameters to allow a more detailed understanding of the internal behavior of the machinery under operation. This has been a successful phase of the project with tests performed at the NWTC 2.5MW dynamometer facility and in the field at the Ponnequin Wind Farm in northern Colorado. An extensive measurement data set has been collected and collated and now serves as an excellent tool for evaluation and improvement of gearbox design and software tools and for understanding the dynamic behavior of gearbox components.

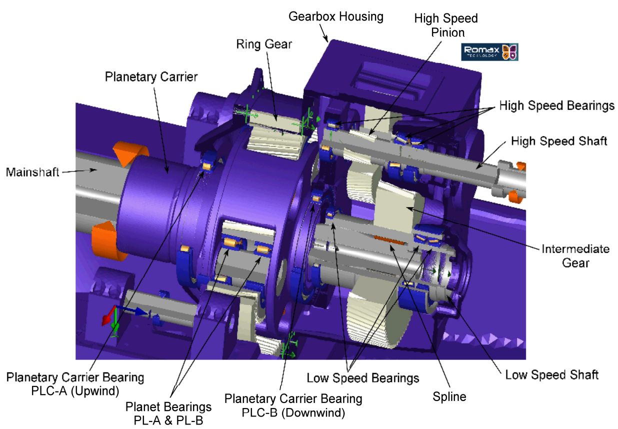
As part of the GRC analysis team, Romax has validated gearbox CAE models against measured planet-to-ring-gear load distributions using RomaxWind software. The correlation is very good, as documented by Wright, et al.[22] and Crowther, et al.[23], confirming that the many parameters and the basic system physics within the gearbox design are accurately modeled with the software tool. These parameters include clearances in planet carrier bearings and planet bearings, gear geometry and microgeometry, whole system structural deflections leading to certain gear and bearing misalignment, weight loading of components, external loading such as wind turbine rotor bending moments and torque, bearing and gear Hertzian contact stiffness and deflections and the flexibility of bearing raceways and gear blanks.

This research on active aerodynamics controls utilizes this GRC 750 drivetrain model because it is validated and it is in the public domain; with such a demonstrated model accuracy, the credibility of the analyses performed here is ensured.

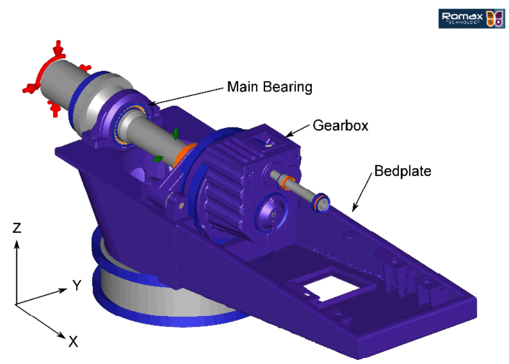
Overview of RomaxWIND modeling and analysis methods

RomaxWIND model of the NREL GRC drivetrain

Figure 4 provides some information on the GRC drivetrain model; Figure 4(a) provides an internal view of the RomaxWIND model of the gearbox, including shafts, gears, bearings and torque arms while Figure 4(b) illustrates the drivetrain layout, including the main shaft, the gearbox and the bedplate. The rotor hub and bedplate are represented as flexible elements in the model. Note that the gearbox design and subsequently the CAE models used for the NREL GRC project have been modified to improve some of the design short-comings outlined in Wright, et al.[22]. Previously reported results by Wright, et al.[22] and Crowther, et al.[23] for gear mesh misalignment between the sun/planet gears and planet/ring gears have been improved by changes to the planetary carrier bearings and to the lead slope corrections applied to the gearing. These improvements to the gearbox allow these studies to focus on the influence of AALC, without the influence of poor design features.



a) Internal View of GRC Gearbox



b) Bedplate Assembly with Coordinates

Figure 4. RomaxWind Model of GRC Gearbox Showing Key Features

Simulation Details

GRC Turbine

The actual GRC turbine is a fixed-pitch, two-speed, upwind, three-bladed, 750kW machine. The NREL FAST model used for the simulations performed in this work is based on the blade and tower properties documented by Bir and Oyague[24]. In order to represent common utility scale controller behavior, the basic GRC turbine model has been extended for this research by the implementation of a Variable-Speed, Variable-Pitch (VSVP) controller.

AALC Devices

AALC devices for this investigation consisted of trailing edge flaps over the outer 25% of the blade span. The flap chord was 20% of blade chord and the flap deflection was limited to +/-10 degrees. The rate of flap actuation was limited at approximately 100 degrees per second. Two-dimensional lift and drag performance of the flapped airfoil sections were calculated with the XFOIL code[25] and modified with the AirfoilPrep tool[26] to include three-dimensional flow effects.

AALC Controllers

A simple PD controller was developed to activate the trailing edge flaps, in conjunction with the conventional VSVP control, to provide effective fatigue load alleviation for this wind turbine. The controller performance index goal maintained maximum power output while minimizing blade-root bending cyclic moments during turbulent wind conditions. No attempt was made to optimize the span-wise placement or extent of the flaps.

A more detailed description of similar AALC controllers developed for a 1.5MW turbine may be found in Wilson, et al.[17]. Wilson found that both tip deflection and tip-deflection rate controllers were effective in reducing the blade-root flap moment fatigue loading, while having little effect on the rotor speed, the low speed shaft torque, the tower base side-to-side and fore-aft moments, and the tower-top yaw moment responses. The tip deflection rate controller was found to be less effective at reducing the blade-root flap fatigue loads, so the tip deflection controller has been used for all the results reported in this paper.

Proportional and derivative gains for the AALC controller were scheduled based on mean incoming wind speed. The gains were chosen to maximize cyclic load reductions while keeping flap actuation rates below approximately 100 degrees per second.

Simulation Procedure

Turbine component fatigue accumulation calculations require time-series load histories at the turbine locations of interest at a number of mean wind speeds spanning the entire operating range of the turbine. For this work, these load histories were generated with structural dynamic simulations of the GRC turbine performed with the NREL FAST structural dynamics code[27], utilizing the NREL AeroDyn aerodynamic code[28] to compute the aerodynamic forces on the blades. FAST utilizes a modal representation of the turbine to determine its response to applied forces, while AeroDyn utilizes the Blade Element Momentum (BEM) representation of aerodynamic loads, relying on airfoil characteristic lookup tables to determine the load at any angle of attack. A dynamic wake model within Aerodyn incorporates the unsteady effects of the wake on the rotor inflow, and a dynamic stall option incorporates certain unsteady effects due to active flap actuations. The Matlab/Simulink[29] control simulation code was used to model both the standard VSVP controller and the AALC control logic for these simulations. The version of AeroDyn that we used was modified to model the effects of blade trailing edge deflection by selecting appropriate alternate lift and drag curves in response to control input from Simulink. All turbine simulations were driven with 10-minute duration, 3-dimensional turbulent wind fields (IEC Normal Turbulence Model, Type A turbulence[30]) generated with the NREL TurbSim code[31].

TurbSim-generated wind fields were created to yield the appropriate mean wind speed and turbulence levels and statistical behavior, but the actual fields depended upon a random seed number – different seed numbers resulted in different wind fields. Six 10-minute simulations were run at each mean wind speed (with different random seeds) to develop representative loads distributions. For this effort, simulations were run at mean wind speeds of 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24m/s.

Processing time-series data for extreme loads

The time series data is processed via search algorithms to construct an extreme loads table. For each force and moment one maximum and one minimum value are found from the combine time histories and recorded. The resultant radial transverse force and off-axis moments are calculated and the maximum/minimum values are also found, yielding an extreme loads table with 16 columns (8 forces, 8 moments). The extreme loads table also records loads in the other directions at the time instant that the extreme load occurs. The analyses apply these loads as well as the extreme load. Note that the extreme loads and results below are described according to the FAST hub non-rotating coordinate system.

Results

Impact of AALC on Extreme Loads

The extreme loads (excluding the resultant minimums) are compared in Figure 5 for the Base case vs. AALC. The reduction in the forces by application of AALC is significant with the greatest reduction being 12% for the thrust force (F_{xmax}), the reduction in the resultant force (combining F_y and F_z) is 9%. The most significant benefit is by large reductions to the off-axis moments, where the resultant of M_y and M_z is reduced by 70%. This has great influence on the limiting stresses in many structural elements as will be demonstrated.

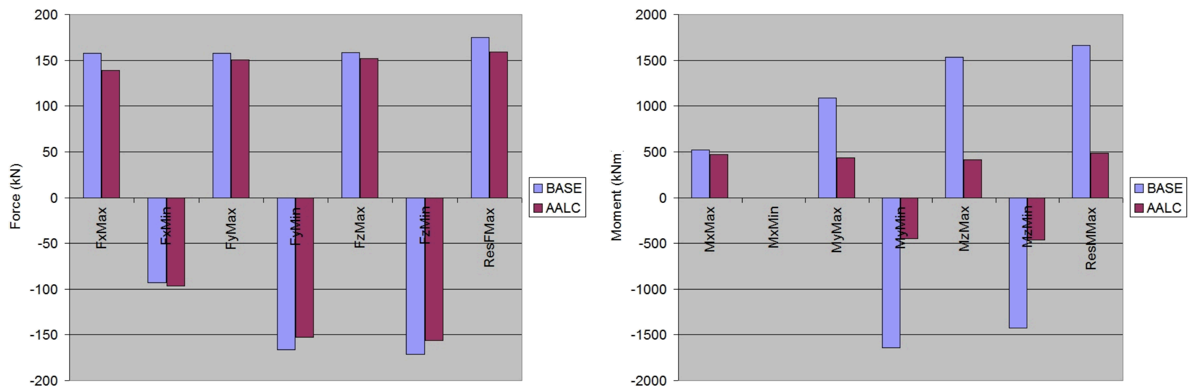


Figure 5. Comparisons for Max/Min Forces and Moments (BASE vs. AALC)

Impact of AALC on Load Carrying Drivetrain Bearings

The main (non-torque) load carrying components in this drivetrain are the main bearing and planet carrier bearings. Within the RomaxWind model a set of analyses are performed for each of the extreme load cases. Each analysis requires a non-linear static convergence for the solution, where the input load at the hub includes the extreme load and corresponding loads in the other dimensions. The analysis incorporates the elastic deflection of the entire structure while solving the contact problem for gears and bearings. Figures 6 and 7 provide the bearing maximum contact stresses for the extreme loads. Adding AALC provides significant improvements. For the main bearing, the maximum contact stresses for the base case fall in the range of 2300-2400MPa for the worst load cases and these are reduced to 1600-1800MPa with AALC. Both planet carrier bearings see a benefit; notably the upwind bearing experiences stress reductions in the order of 50% for the extreme moment load cases. The highest stress case (the limiting case) for the upwind carrier bearing is reduced from 2693MPa to 1250MPa.

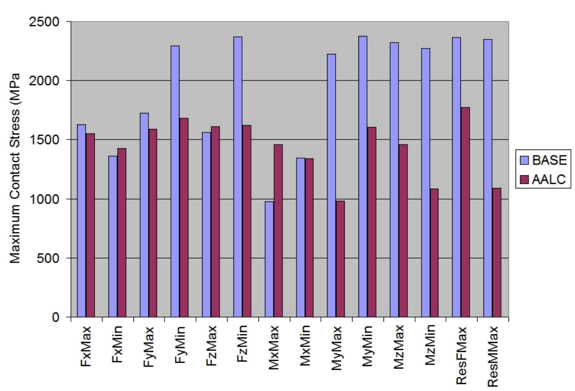
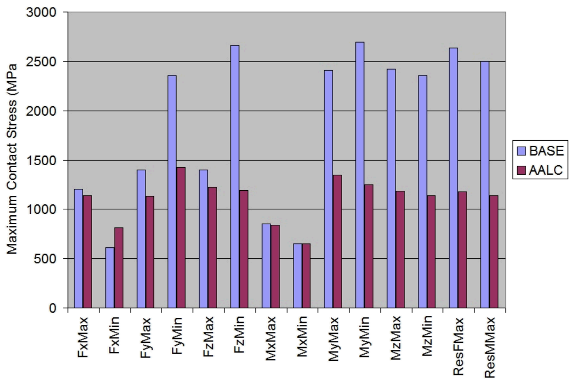
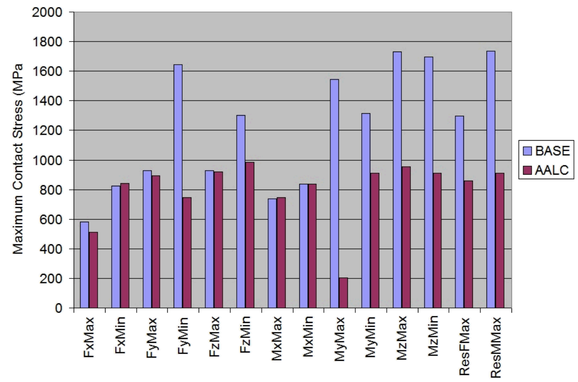


Figure 6. Main Bearing Contact Stress Results (BASE vs. AALC)



a) Upwind



b) Downwind

Figure 7. Planetary Carrier Bearing Contact Stress Results (BASE vs. AALC)

Studies on the improvements in fatigue life for the structural and machine elements are on going, but some initial results are reported for the bearings. For these calculations a fatigue load spectra in multiple dimensions is determined and for each load case in the spectra the non-linear static analysis is performed with the RomaxWind model. The analysis results provide bearing loads and loaded contact distributions as well as other factors. These results are used to perform the fatigue calculations according to ISO 281[32] (and DIN ISO 281 Supplement 4). Table 1 provides a brief summary of the results for the bearings; it shows reductions in the fatigue damage as a result of the implementation of AALC, in particular, the upwind carrier bearing shows a reduction of 32%. Additional details and results are presented in the Romax project report[33].

The AALC provides a remarkable improvement to the limiting stresses and fatigue for these load carrying bearings, which would allow for a smaller, lower cost bearing and support structure in a new design or improved reliability and life when implemented to an existing design.

Bearing	**Relative Change in Fatigue Damage due to AALC**
Main	-7%
Upwind Carrier	-32%
Downwind Carrier	-16%

Table 1. Impact of AALC on Gearbox Bearing Fatigue Damage

Impact of AALC on Extreme Load Cases on the Bedplate

Part of this research is to quantify the benefits of AALC to the supporting structures such as rotor hub, housings and bedplate. Here the bedplate stresses are studied for the extreme load cases with maximum moments M_x, M_y and M_z (also with the loads in other directions that occur at the same time instant). A set of results are shown in Figures 8-10; the loads are applied at the hub in the RomaxWind model and are reacted onto the bedplate through the main bearing and gearbox mounts (elements apart from the hub are hidden). The bedplate is constrained at the base. For the maximum M_x, which is torque, there is little benefit gained; AALC is not reducing the maximum torque experience by the drivetrain. For the maximum off-axis moments (M_y and M_z) the benefits are again dramatic with significant reductions in the stresses at critical regions of the structure.

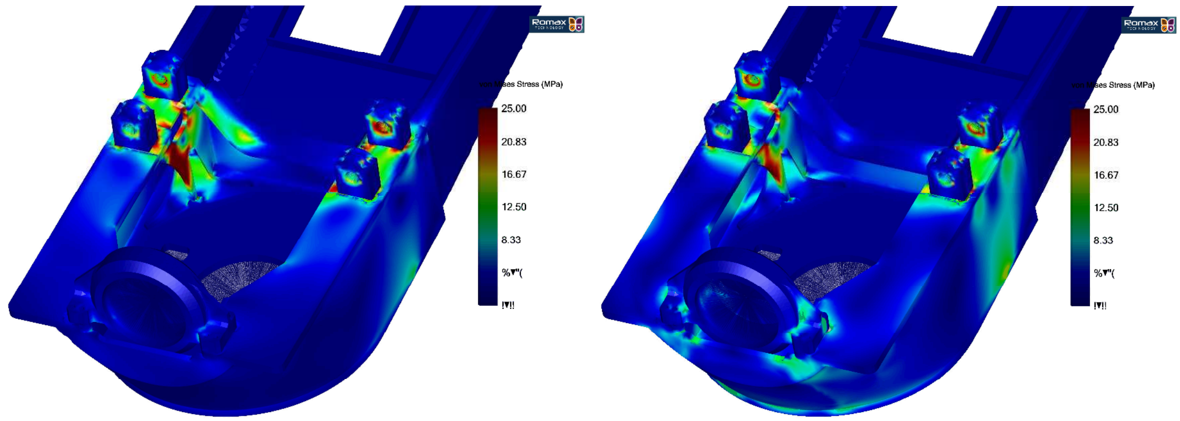


Figure 8. Bedplate Stress Results for Max Moment About X-Axis (BASE vs. AALC)

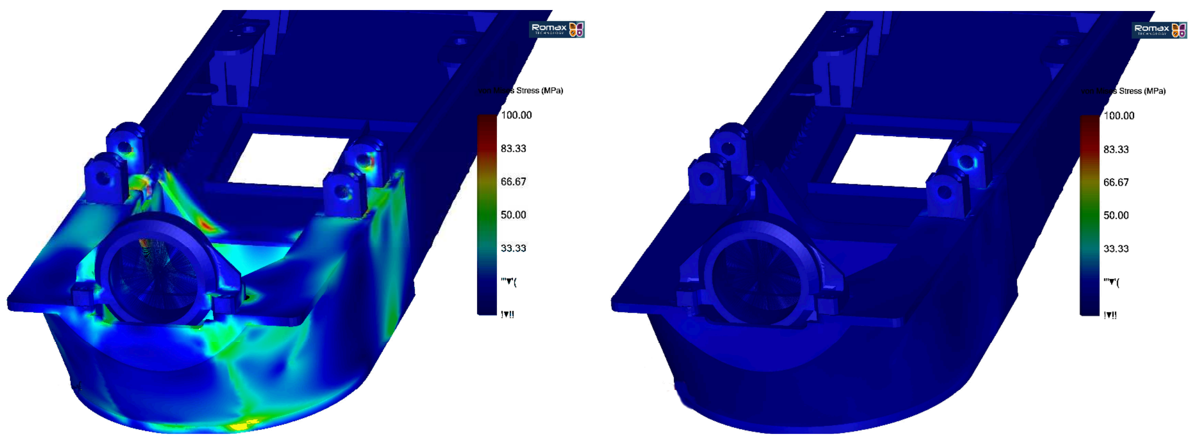


Figure 9. Bedplate Stress Results for Max Moment About Y-Axis (BASE vs. AALC)

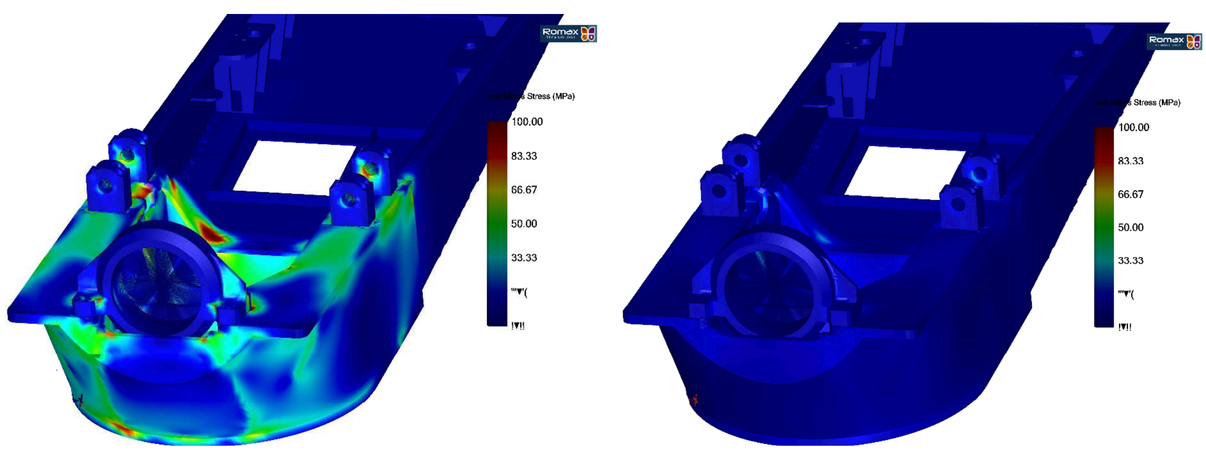


Figure 10. Bedplate Stress Results for Max Moment About Z-Axis (BASE vs. AALC)

Conclusions, Summary and Future Work

This research reports a portion of the results on a project undertaken to determine the impact of AALC on various components in the wind turbine structural load path. The research demonstrated that AALC significantly reduces the extreme loads that would be applied to the design calculations to confirm satisfactory component stresses versus limit criteria. A detailed computational model of the turbine drivetrain, including contact mechanics for the machine elements and elastic structures for bedplate, hub, gearbox housings and shaft, was applied to quantifying such stresses. Sets of analysis were performed for extreme loads cases and demonstrated significant improvements when AALC was implemented. In particular cases bearing static stresses for limiting cases were reduced by as much as 50%. Fatigue analysis showed improvements between 7 and 32% for the load carrying bearings. The AALC blade load control strategy brings benefits to components throughout the structural load path, as is demonstrated by an analysis showing reduction in bedplate stresses under extreme loads. The greatest advantage for the turbine appears to be the reduction of the off-axis moments, which are often the design limiting loads for strength.

This work clearly demonstrates that AALC has great potential to reduce ultimate and fatigue loads throughout the drivetrain of a turbine. Additional efforts on this project will look at the impact of AALC on fatigue damage on other drivetrain components. In future work we plan to examine the impact of AALC on turbine cost of energy and investigate the sensitivity of these results to drivetrain details (different main shaft, gearbox and bedplate configurations) and turbine size.

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