Advanced Wind Turbine Drivetrain Topology for Improving System Reliability

Cooperative Research and Development Final Report

CRADA Number: CRD-10-400

NREL Technical Contact: Jeroen van Dam

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-77552
August 2020

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Cooperative Research and Development Final Report

Report Date: 3/30/2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Alstom Power, Inc.

CRADA Number: CRD-10-00400

CRADA Title: Advanced Wind Turbine Drivetrain Topology for Improving System Reliability

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$.00
TOTALS	$.00

Abstract of CRADA Work:

Alstom Power has a desire to locate its latest entrance into the U.S. market at a location that truly tests the durability of the machine in a turbulent environment as well as verify the basic operating characteristics of the machine on a 60 Hz grid. The DOE/NREL National Wind Technology Center (NWTC) is well suited for this goal. The DOE/NREL Wind Program is working on improving drivetrain reliability through its Gearbox Reliability Collaborative (GRC). Alstom is also interested in performing research on their innovative drivetrain that is aligned with the objectives of the GRC. The tasks outlined in this Joint Work Statement are intended to accomplish these goals to the mutual satisfaction of both parties and the advancement of the understanding of wind turbine drivetrain behavior.

Summary of Research Results:

The purpose of this section is to capture the original or modified scope, completed work and outcomes of this project. DOE requires that this template address all the planned tasks in the Joint Work Statement.

Original CRADA:

Task I: Turbine installation

Alstom provided the electrical and civil design drawing to NREL for their review. NREL provided project management and safety oversight for the development of the site and construction of the turbine. Upon completion of the construction and commissioning of the turbine NREL and Alstom hosted a commemoration event was held: https://www.nrel.gov/news/press/2011/976.html

Figure 1. Installation of the ECO100 nacelle

Figure 2. Dana Christensen (NREL), Andy Geissbuehler (Alstom) and Steve Chalk (DOE) at the turbine dedication event (PIX 31656)

<u>Task II Testing in support of certification of turbine</u>

All testing required to obtain certification of the 60Hz version of the Alstom ECO 100 wind turbine was completed. Accredited test reports for power performance, acoustics, power quality were provided to Alstom which were passed on to their certification body resulting in the type certification of the turbine type.

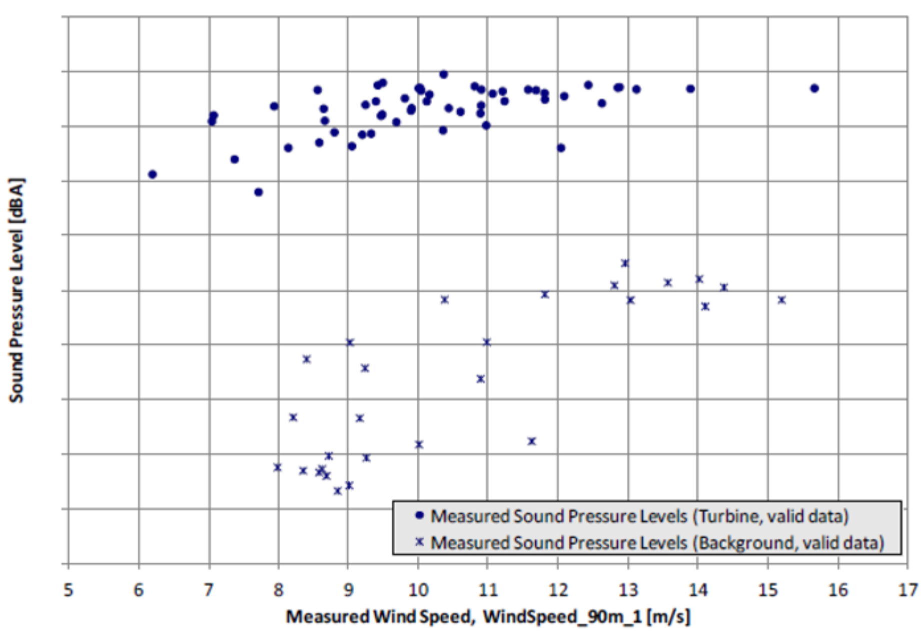


Figure 3. Example of measured acoustic sound pressure levels

Task III: Drivetrain modelling and analysis

NREL collaborated with Alstom to develop a model of the drivetrain using SAMCEF and FAST. NREL also developed an analytical model of the drivetrain. Finally, NREL collected data on the turbine installed at the NWTC. Work was done to compare the measured and model data to demonstrate the advantages of the Alstom Pure Torque drivetrain which protects the gearbox from non torque loads. Comparisons were also made to the Gearbox Reliability Collaborative data which captures a more typical three-point suspension drivetrain configuration.

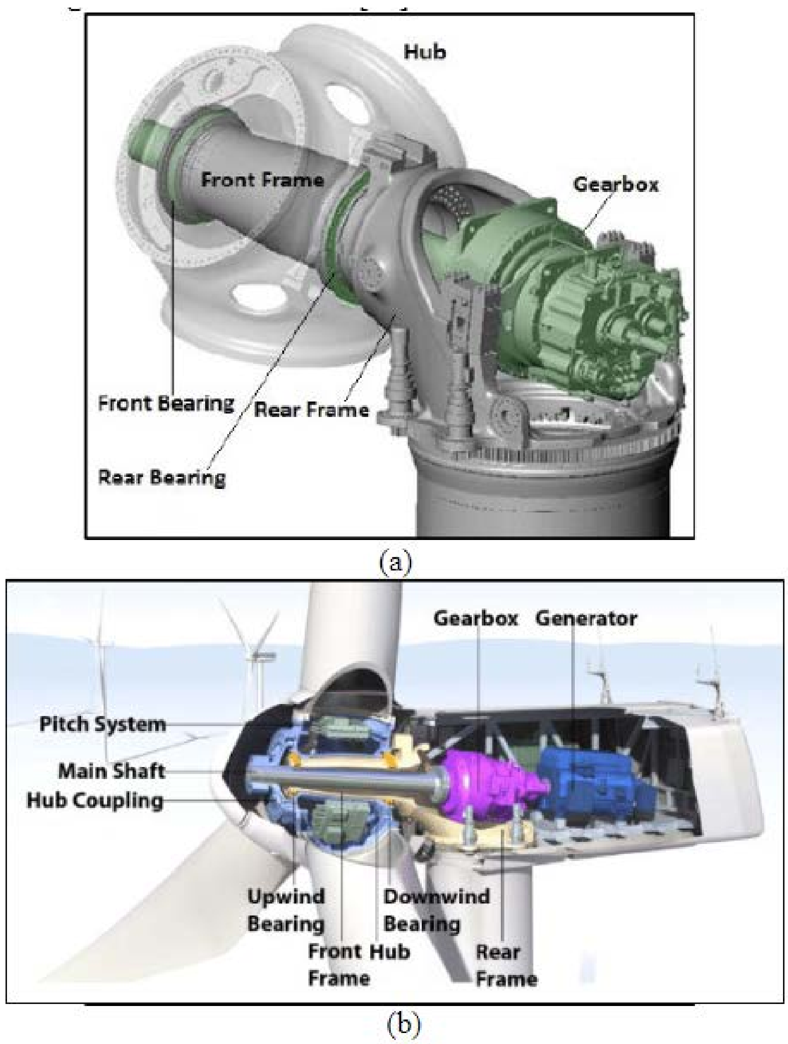


Figure 4. (a) Alstom's Pure Torque drivetrain (b) hub support

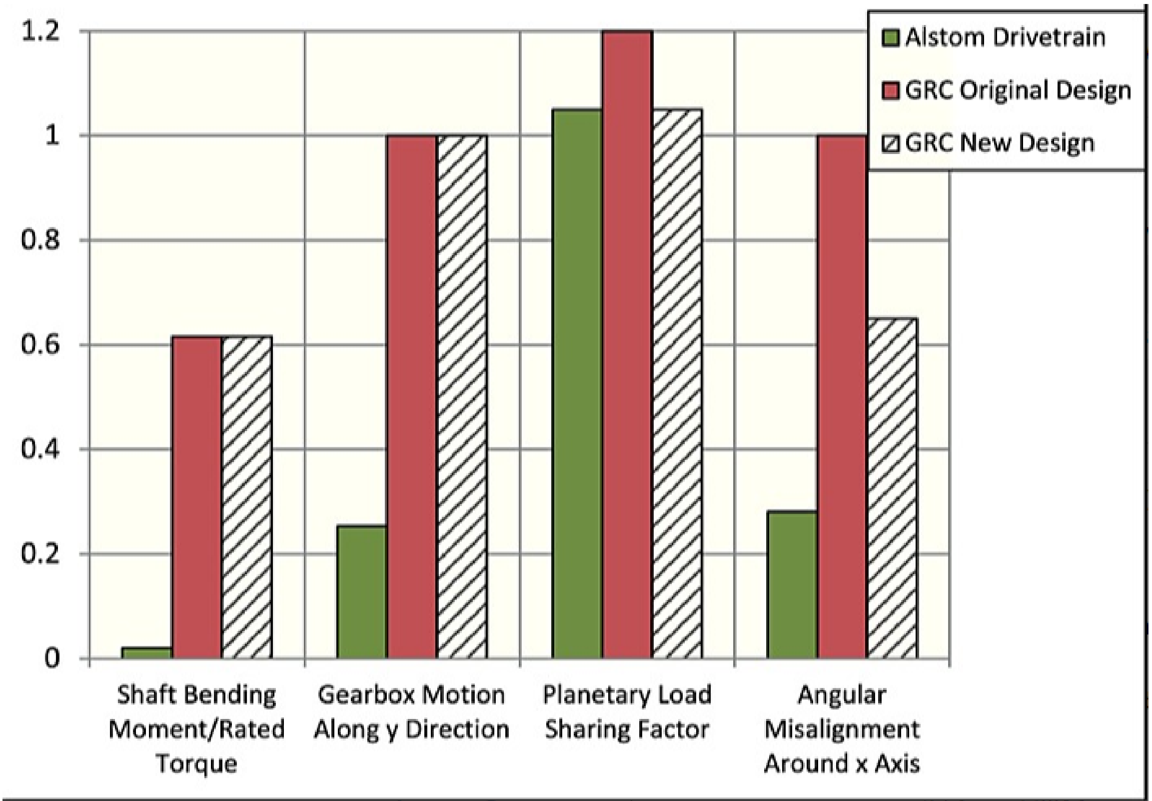


Figure 5. Plot showing key drivetrain design parameters for the Alstom pure torque drivetrain compared to the GRC drivetrains

The work resulted in several posters, conference presentations and a journal publication (development of which was further funded under Mod 5):

Y. Guo, R. Bergua, J. van Dam, J. Jove, J. Campbell; Improved wind turbine drivetrain designs to minimize the impacts of non-torque loads; Wind Energy, 18 (12) (2015), pp. 2199-2222

Guo, Y, Bergua, R, Dam, J, Jove, J, Campbell, J. Improving wind turbine drivetrain reliability using a combined experimental, computational, and analytical approach. In ASME IDETC, 2014.

Task IV: Long term testing to predict ultimate and fatigue loads, transient loading testing

This task was cancelled by the partner.

Task V: Turbine and foundation removal:

The turbine and foundation were removed in the summer of 2018. The tower was cut into pieces and recycled. The site was remediated to NREL specifications including removal of part of the road and the crane pad and reseeding of the area.

https://www.nrel.gov/news/program/2018/research-turbine-leaves-legacy-in-its-wake.html

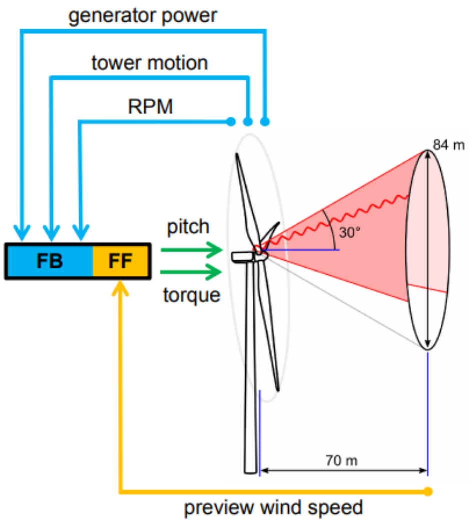
https://www.ge.com/reports/testing-testing-colorado-turbine-helped-ge-expand-wind-business/

Figure 6. Foundation removal

Mod 1:

phase I: LIDAR assisted control strategies:

Alstom and NREL worked collaboratively to develop lidar assisted control strategies.



Schematic of LIDAR feed-forward control system.

The most promising controls approach was implemented by Alstom on the ECO100 wind turbine at the NWTC. The validation task (1.2) was not executed and removed as part of mod 3. This task was solely executed by Alstom.

Figure 7. Lidar installed on nacelle roof of ECO110 wind turbine at NREL

Results of the work were disseminated in reports and at conferences. The work was also used in support of Na Wang's PhD dissertation: https://mountainscholar.org/bitstream/handle/11124/20/Wang_mines_0052E_10333.pdf?sequence=1

Ehrmann, Robert, Wang, Na, Wright, Alan, Guadayol, Marc, Scholbrock, Andrew, and Arora, Dhiraj. Development, Field Testing, and Evaluation of LIDAR-Assisted Controls. United States: N. p., 2015. Web.

Ehrmann, Robert, Guadayol, Marc, and Arora, Dhiraj. Turbine Mounted LIDAR Validation. United States: N. p., 2015. Web.

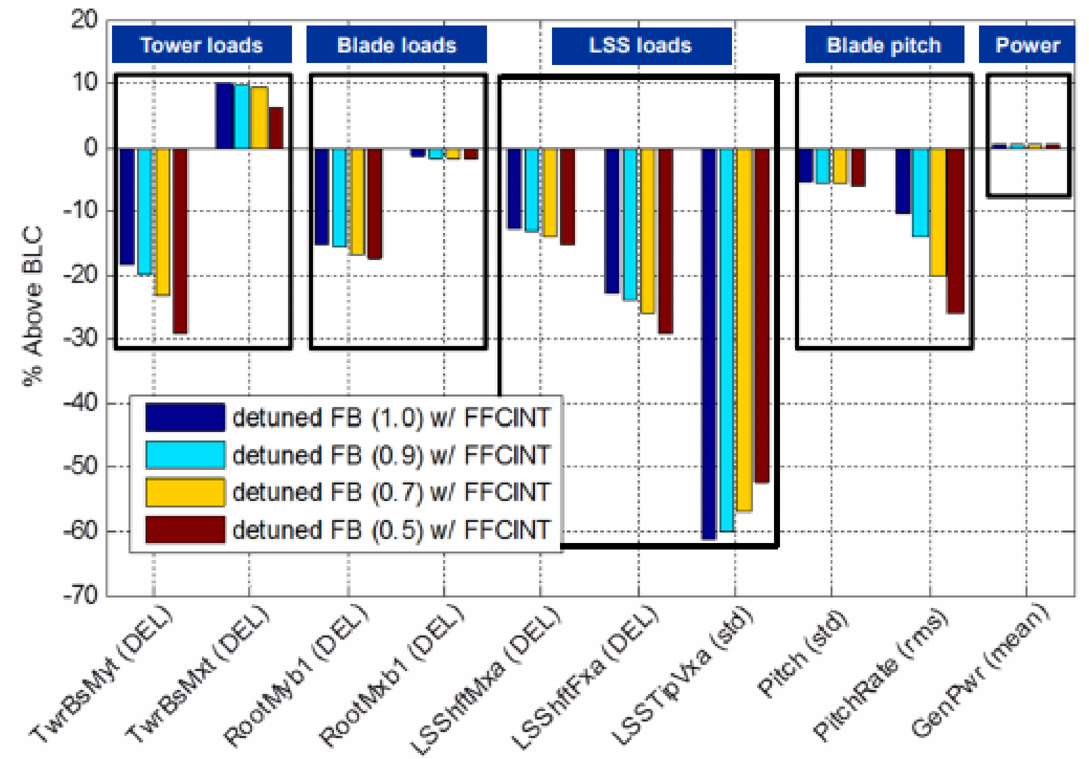


Figure 8. Key performance metrics comparing lidar assisted feed forward controls to the baseline controller.(BLC)

phase2: Advanced controls for offshore wind turbines

This task was executed and was later augmented with other tasks once Alstom was awarded a FOA 415 award. The task resulted in the following publication showing three different controllers:

Fleming PA, Pineda I, Rossetti M, Wright AD, Arora D. Evaluating Methods for Control of an Offshore Floating Turbine. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 9B: Ocean Renewable Energy ():V09BT09A019. doi:10.1115/OMAE2014-24107.

Mod 2:

Mod 2 added work related to the dynamic characterization of the ECO86 wind turbine located in Lubbock Texas. NREL staff traveled out to Lubbock to instrument the turbine and conduct as series of modal test experiments. Excitation was done through modal hammers and snapback tests. The modal test results were documented in a report which was provided to Alstom. Figure 9 shows the set up of the snap back test. Figure 10 shows the results.

Figure 9. Snapback excitation on the ECO86 turbine in Lubbock

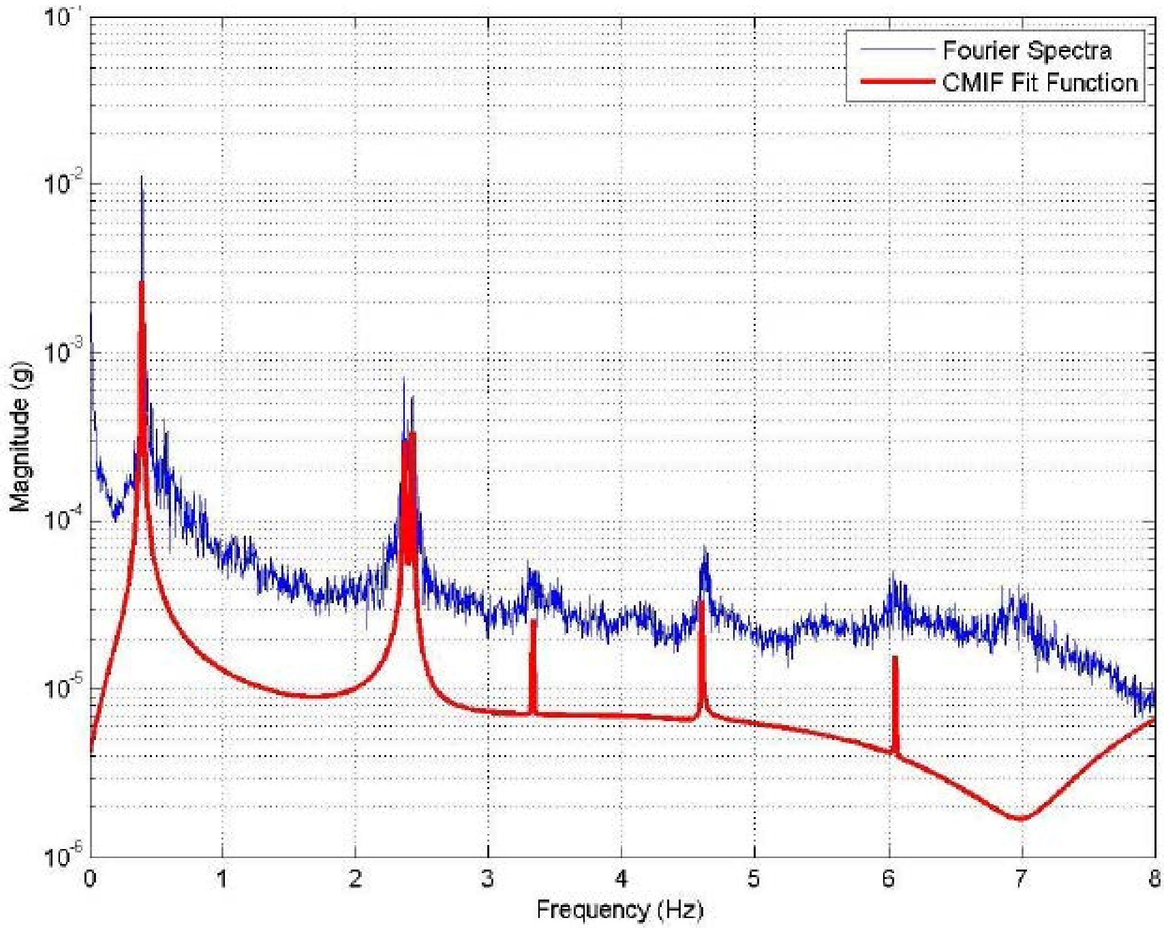


Figure 10. FFT results of snap back test

<u>Mod 3:</u>

Advanced wind turbine control strategies:

<u>Task 1: State Space Feedback controller design for ECO100</u>

NREL worked with the Colorado School of Mines to develop control strategies under this task the outcome of which is covered in part by Na Wang's PhD dissertation: https://mountainscholar.org/bitstream/handle/11124/20/Wang_mines_0052E_10333.pdf?sequence=1
More controller details were provided directly to Alstom in the form of Simulink files.

<u>Task 2: Modeling of the Haliade 6MW turbine on a Tension Leg Platform</u>

This work was part of a DOE FOA 415 award that Alstom won. NREL worked with Alstom and the other team members to complete this task. NREL developed models of the Haliade turbine on the Glosten Pelastar TLP showing a 70% reduction of tower base fatigue loads and 25% reduction in tendon tension fatigue loads without impacting Annual Energy production.

Several of the tasks in the CRADA related to the FOA 415 award were presented at the FY17-18 DOE wind program peer review: https://www.energy.gov/sites/prod/files/2019/05/f63/GE%20-%20T25%20-%20Arora%20Murray%203%205%2019%20v4.pdf

Mod 4:

Task 1: Support for installation on the new rotor

In 2010 Alstom changed the blades on the ECO100 with longer blades turning the ECO100 into an ECO110 wind turbine. NREL supported this activity with project management and safety support.

Figure 11. AL 53 blades being prepared for installation on the ECO100 wind turbine

Task 2: Accredited IEC testing in support of the ECO110 certification

NREL conducted a series of accredited test in support of the certification of the 60Hz version of the ECO110 wind turbine. This test program consisted of Power performance in accordance to IEC 61400-12-1, mechanical load measurements in accordance with IEC 61400-13, acoustic noise in accordance with IEC 61400-11 and safety and function in accordance with IEC WT 01. The results of these tests were documented in confidential accredited reports. The reports were passed on to the certification body and resulted in the certification of the ECO110 wind turbine for the U.S. market.

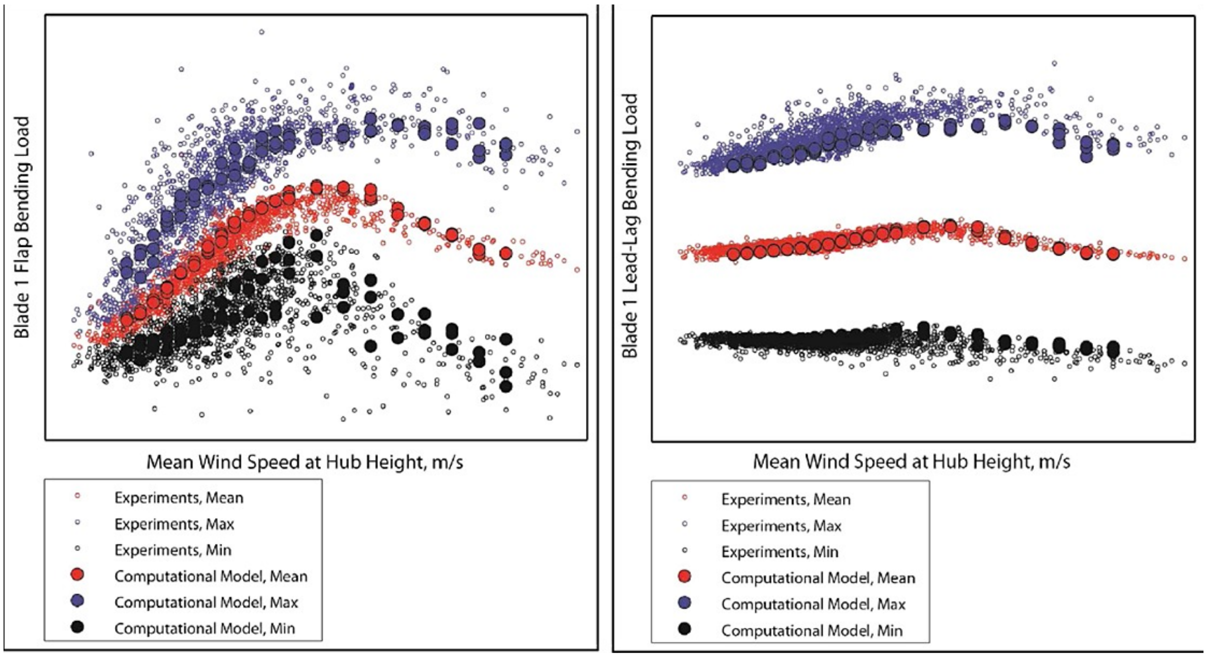


Figure 12. Scatterplot of measure blade root bending moments on the ECO100 and comparison to computation models used for the drivetrain analysis tasks

Mod 5:

Modelling of Alstom 6MW Haliade offshore wind turbine using SAMCEF

This task was used to wrap up the ECO100 drivetrain modeling work and finish the journal article:

Y. Guo, R. Bergua, J. van Dam, J. Jove, J. Campbell; Improved wind turbine drivetrain designs to minimize the impacts of non-torque loads; Wind Energy, 18 (12) (2015), pp. 2199-2222

It then has four tasks related to the modeling of the Haliade 6MW wind turbine using SAMCEF modeling software:

1. Analytical formulation of Haliade pure torque drivetrain
2. Evaluation of frame flexibility using SAMCEF
3. Comparison of SAMCEF models with different degrees of fidelity
4. Project report

The first three tasks were completed but Alstom decided to not spend the resources on the final reporting. Figure 13 shows the layout of the halide wind turbine nacelle. Figure 14 shows the Haliade SAMCEF model. The impact of frame stiffness modelling on resulting frame loads is shown in Figure16. A summary of the results comparing the different fidelity models to experimental data is seen in Figure 15

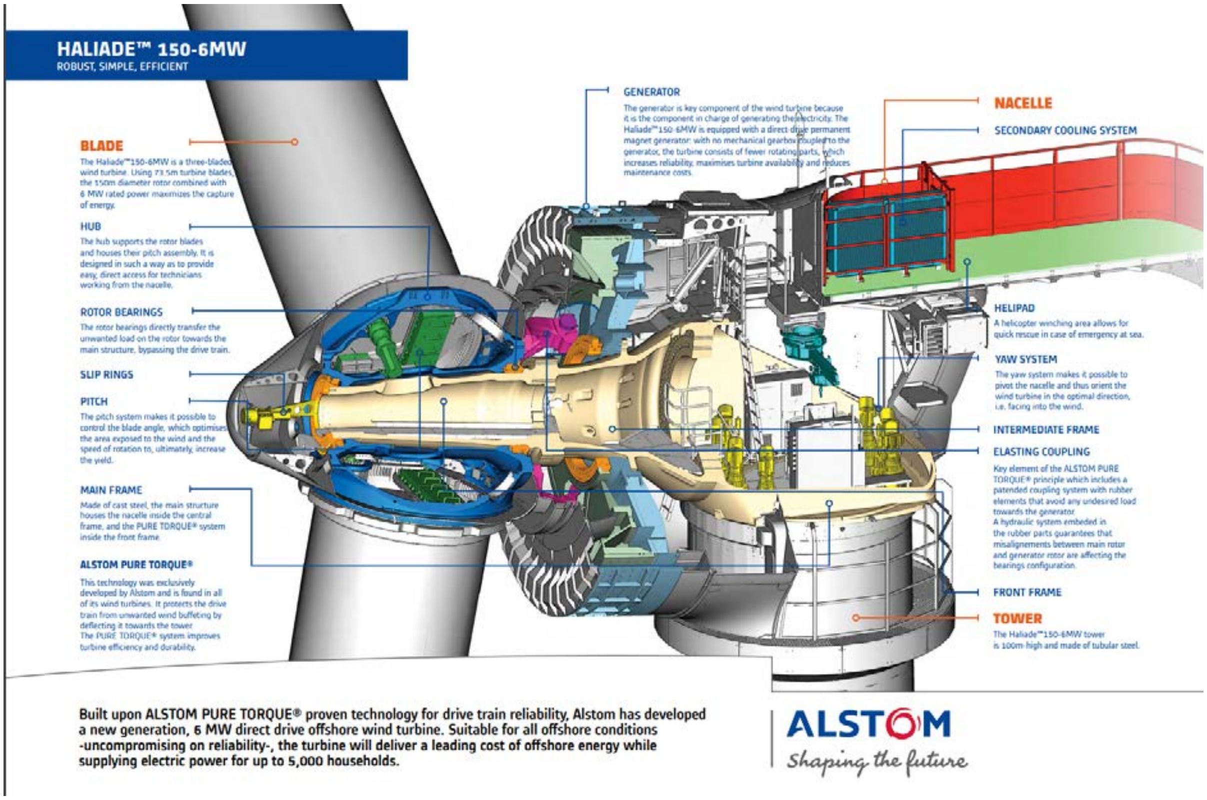


Figure 13. Overview of Alstom Haliade turbine

Figure 14 SAMCEF model of Haliade turbine

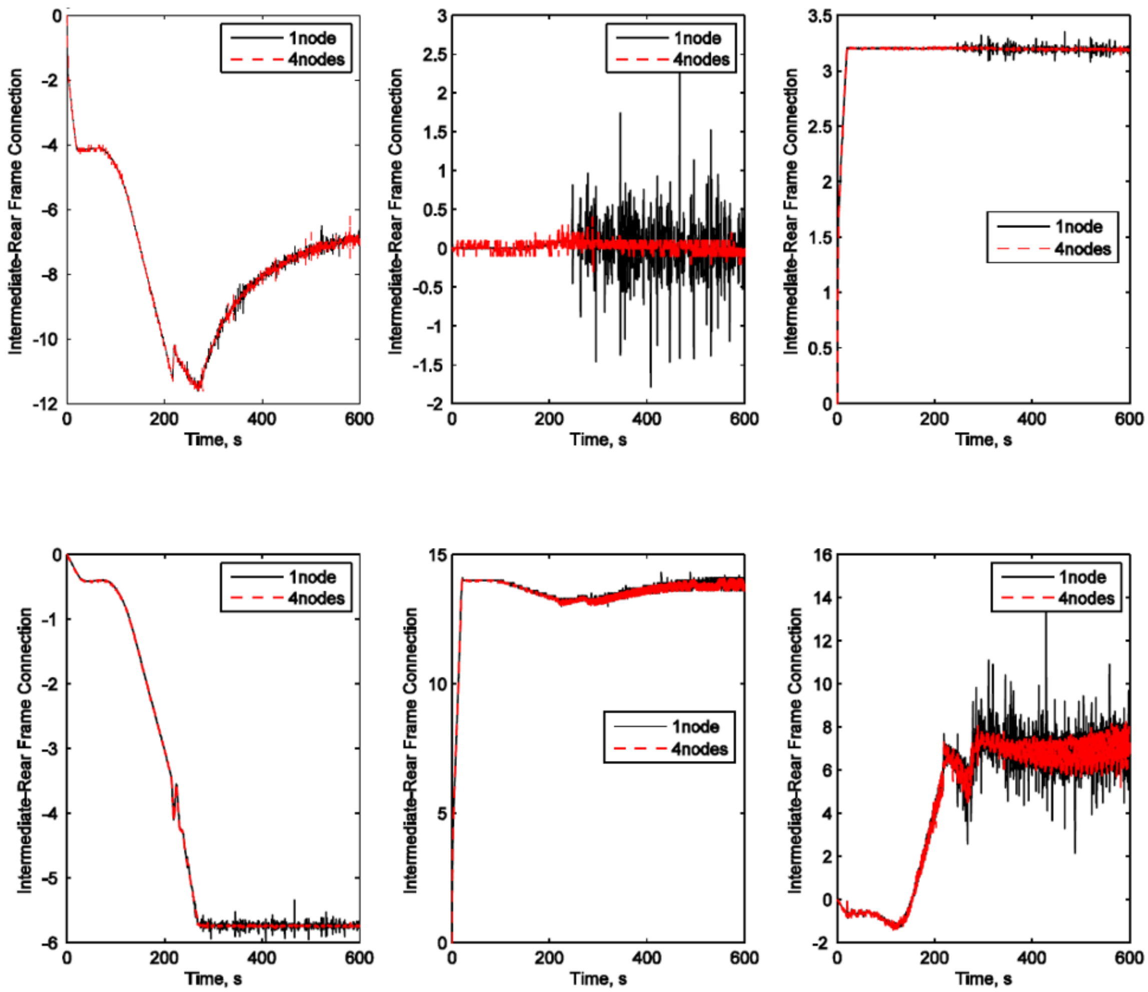


Figure 155. Effect of drivetrain stiffness modelling on frame loads

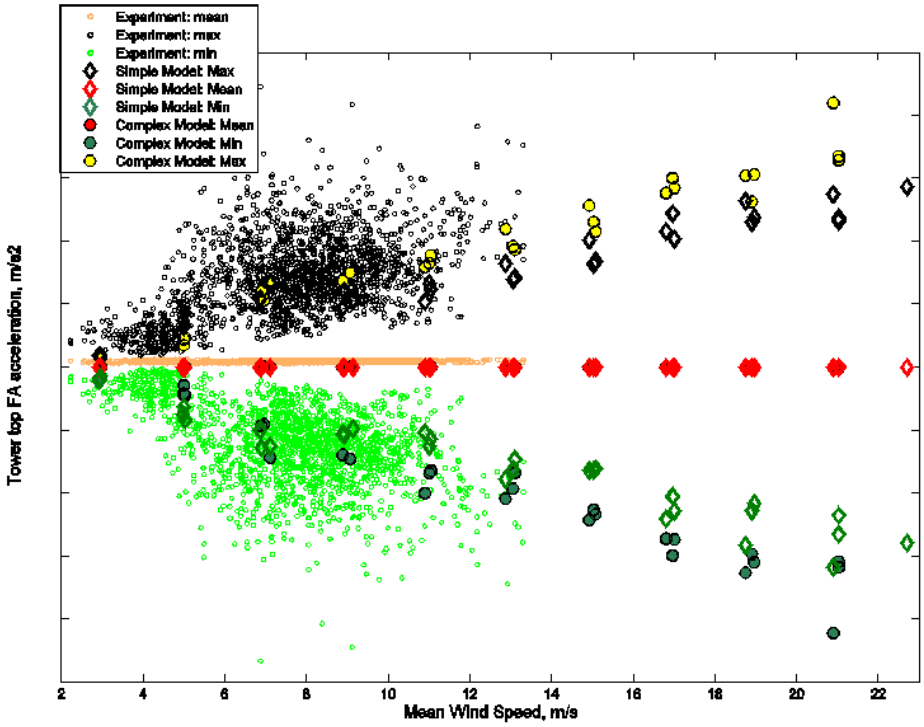


Figure 166. Plot showing comparison of experimental data with the simple and complex model for tower top acceleration

Mod 6:

Flow visualization of Alstom ECO110 blades; baseline and after flow control implementation

Under this modification NREL performed flow visualization on the Alstom ECO110 wind turbines blades before and after the addition of flow modifiers to the blades. NREL designed a pattern for pieces of yard that were attached to the blades using rope access. NREL then took pictures of the tufts under a range of operating conditions. This was repeated after Alstom installed flow modifiers to the blade (such as vortex generators and spoilers) to validate the Alstom flow models. NREL provided the results in a report to Alstom:

Tuft Flow Visualization of the Alstom AL53 Blade with Vortex Generators and Spoilers; S. Schreck, L. Fingersh, and J. van Dam

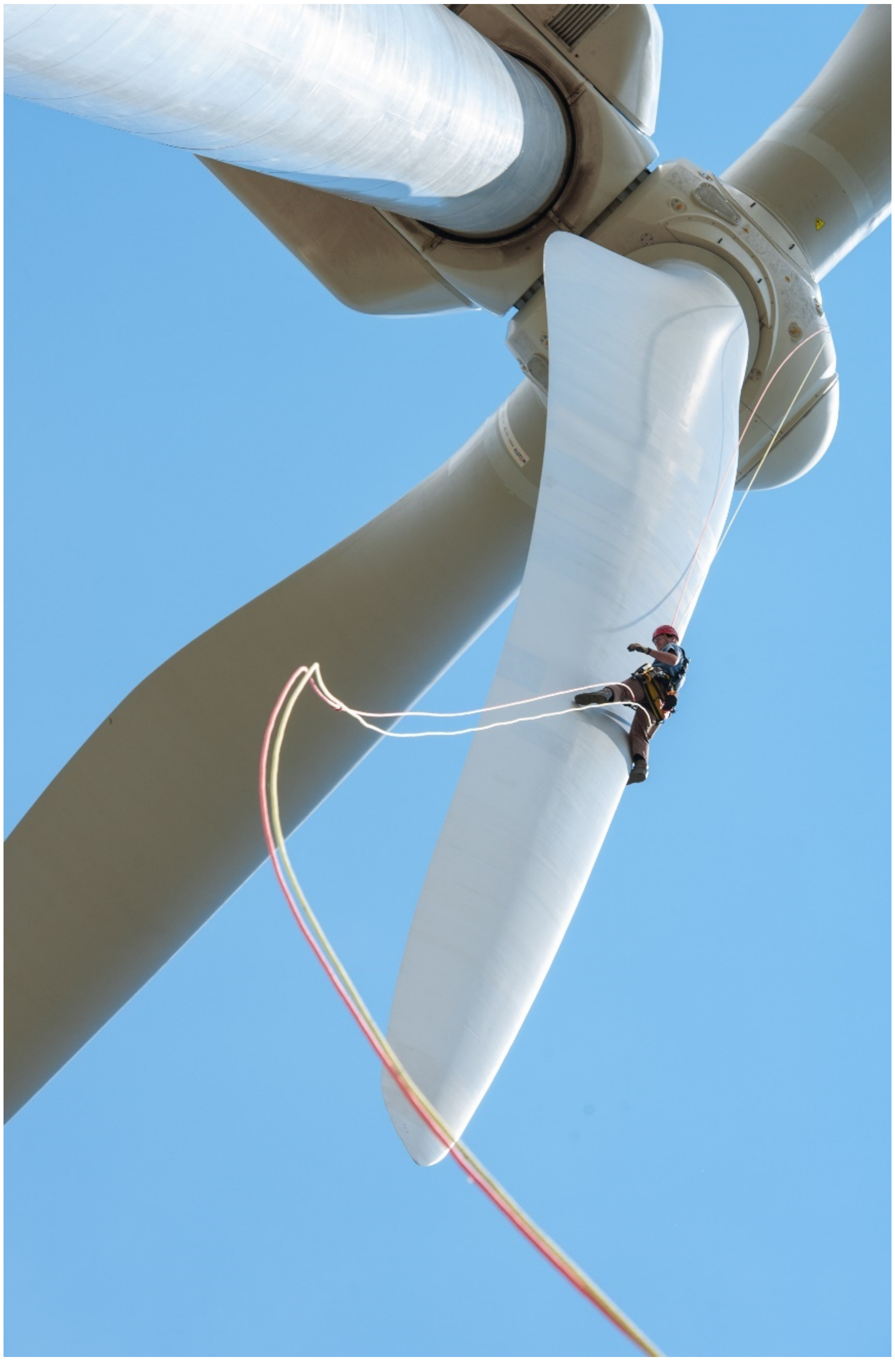


Figure 17. Rope workers installing tufts on the Alstom ECO110 blades (NREL PIX: 27196)

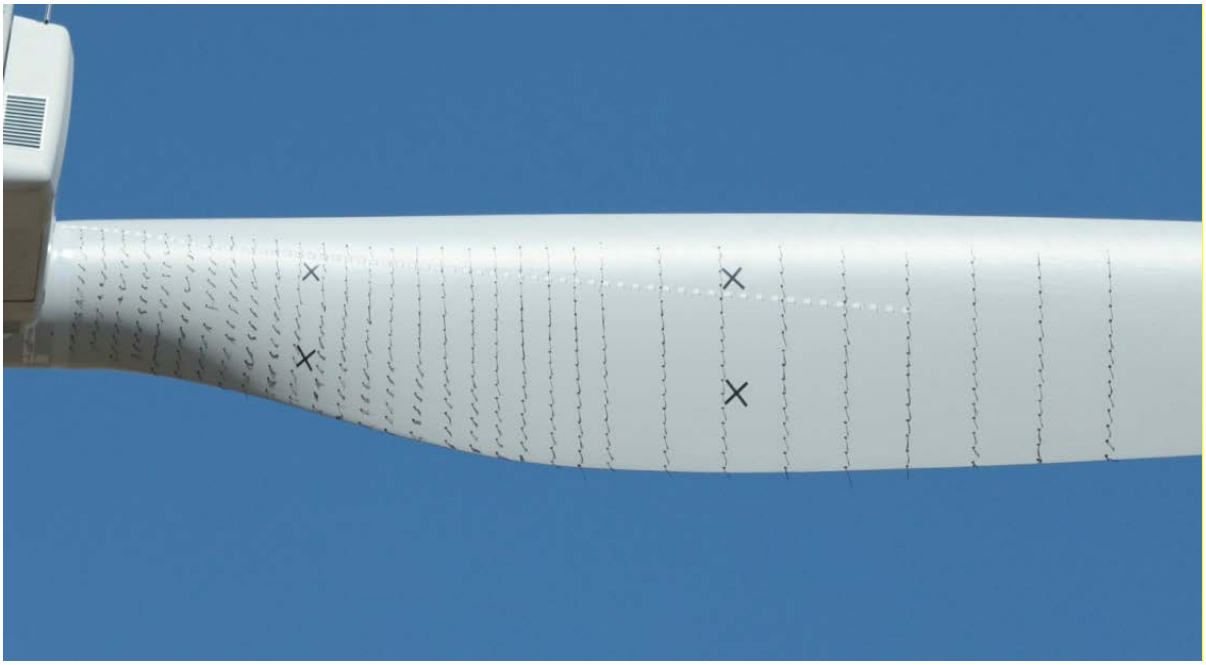


Figure 18. Tufts on the Alstom ECO110 turbine showing air flow

<u>**Mod 7:**</u>

Modified the loaned property Appendix to include the new blades and lidar.

<u>**Mod 8:**</u>

Generator validation testing on the ECO110 wind turbine

Alstom replaced the wind turbine generator with two new generator models from different vendors. NREL supported the vendor qualification work by taking vibration data on both generators. A test report was provided to Alstom for each generator documenting the vibration levels under a range of operating conditions.

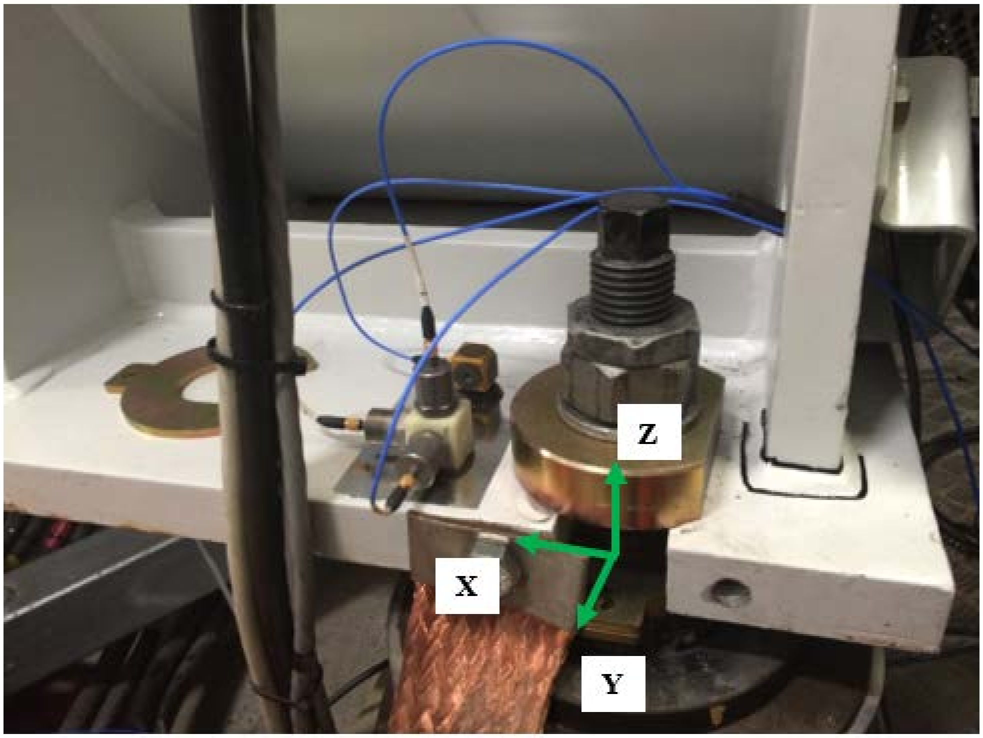


Figure 19. Accelerometers mounted in support of the generator vibration testing.

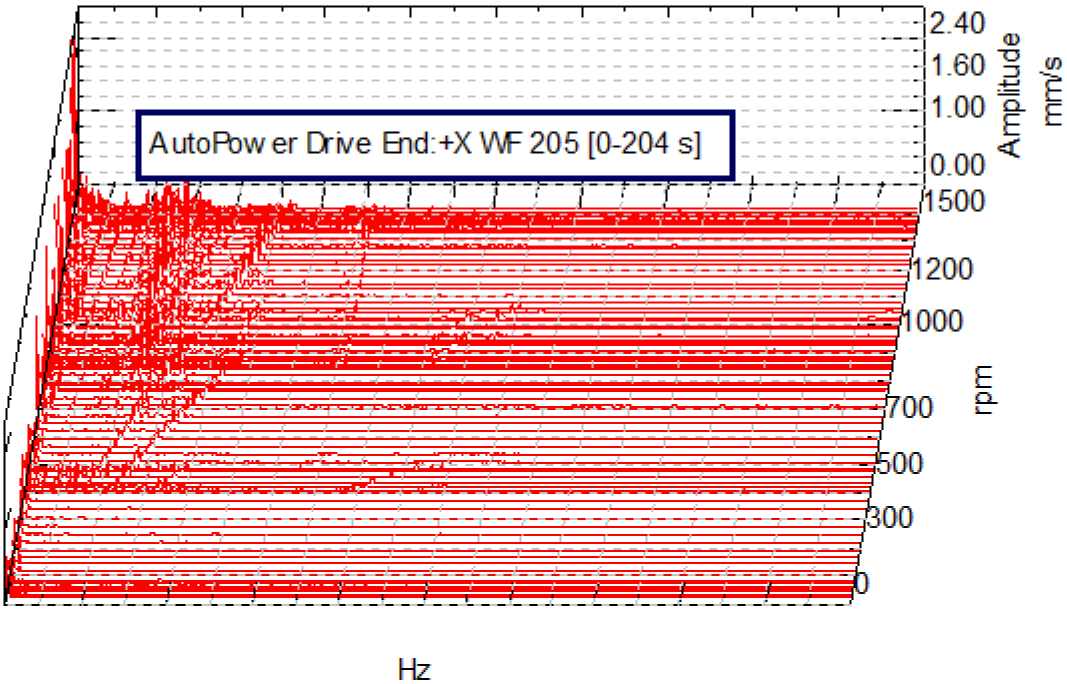


Figure 20. Example of waterfall plot showing frequency response as a function of rotor speed

Mod 9:

Mod 9 added more time to the period of performance

Mod 10:

Toggle brace damper system validation with SAMCEF

Although the intention lists SAMCEF as the desired modeling tool. NREL used ANSYS instead. NREL also assisted in the validation of the FAST model that UMass developed with the damper system incorporated. This FAST model was then used by Alstom and UMass for a series of publications. The modeling and analysis showed that the toggle brace damper has the ability to significantly lower tower loads, as explained in the following published reports:

https://www.osti.gov/servlets/purl/1254149

https://www.osti.gov/biblio/1238146-floating-offshore-wtg-integrated-load-analysis-optimization-employing-tuned-mass-damper

Mod 11:

Mod 11 added more time to the period of performance

Mod 12:

Tower damper field testing

This task had Alstom design and install three dampers that would attach between the tower and foundation of the ECO110 wind turbine at the NWTC (National Wind Technology Center). NREL instrumented the columns and dampers and calibrated the supporting columns in the dynamometer. Data was provided back to Alstom who did the data processing and model comparison. This work was part of the Alstom FOA 415 award.

Figure 21. Installation of tower dampers

Mod 13 and 14:

These mods added time to the period of performance to allow for the execution of task V under the original CRADA: Turbine and foundation removal.

Subject Inventions Listing:

None

ROI #:

None

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DOE Program Office:

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Wind and Water Technologies Office