Aero-Elastic Optimization of a 10 MW Wind Turbine

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Boulder, CO, USA

Analysis and Design Wind Turbines

- Analysis codes for predicting the performance of wind turbines are well established both in the research community and industry, e.g:
  - Aero-elastic codes based on BEM methods and finite beam element models,
  - Panel codes, 2D/3D CFD for the prediction of aerodynamic performance,
  - 2D/3D FEM for prediction of cross-sectional/full blade structural performance,
- While these tools are all used stand-alone to design turbines, their use in combination with a multidisciplinary optimization (MDO) framework is not widely spread neither in research or industry.
- Pioneered in the aerospace industry, multidisciplinary optimization (MDO) has been shown to be effective for systematically exploring the design space and tailor designs according to very specific requirements, e.g. load mitigation using material and geometric couplings.

This Talk

This talk will discuss the efforts currently in progress towards realizing an *Integrated Framework For Optimization of Wind Turbines* at DTU Wind Energy and its application to the design of a 10 MW wind turbine rotor.

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Reseach Question

What are the multidisciplinary trade-offs between rotor mass and AEP for a 10 MW rotor mounted on the DTU 10MW RWT platform?

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Introduction
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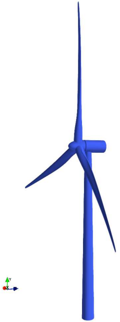
Reseach Question

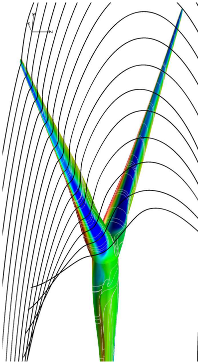
What are the multidisciplinary trade-offs between rotor mass and AEP for a 10 MW rotor mounted on the DTU 10MW RWT platform?

- DTU 10MW Reference Wind Turbine,
- Overview of the optimization framework,
- Optimization cases:
  - Structural optimization of the rotor,
  - Aero-structural optimization of the rotor,
  - Fatigue constrained aero-structural optimization of the rotor,
  - Frequency constrained aero-structural optimization of the rotor.
- Conclusions.

Previous Work
The DTU 10MW Reference Wind Turbine

- Fully open source, available at http://dtu-10mw-rwt.vindenergi.dtu.dk,
- Detailed geometry,
- Aeroelastic model,
- 3D rotor CFD mesh,
- Detailed structural description, ABAQUS model,
- 300+ users,
- Used as reference turbine in the EU projects INNWIND.eu, MarWint, and IRPWIND, among others.





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Previous Work
The DTU 10MW Reference Wind Turbine

Parameter	Value
Wind Regime	IEC Class 1A
Rotor Orientation	Clockwise rotation - Upwind
Control	Variable Speed
	Collective Pitch
Cut in wind speed	4 m/s
Cut out wind speed	25 m/s
Rated wind speed	11.4 m/s
Rated power	10 MW
Number of blades	3
Rotor Diameter	178.3 m
Hub Diameter	5.6 m
Hub Height	119.0 m
Drivetrain	Medium Speed, Multiple-Stage Gearbox
Minimum Rotor Speed	6.0 rpm
Maximum Rotor Speed	9.6 rpm
Maximum Generator Speed	480.0 rpm
Gearbox Ratio	50
Maximum Tip Speed	90.0 m/s
Hub Overhang	7.1 m
Shaft Tilt Angle	5.0 deg.
Rotor Precone Angle	-2.5 deg.
Blade Prebend	3.332 m
Rotor Mass	227,962 kg
Nacelle Mass	446,036 kg
Tower Mass	628,442 kg
Airfoils	FFA-W3

Table: Key parameters of the DTU 10 MW Reference Wind Turbine.

New Framework for Multi-Disciplinary Analysis and Optimization

Based on previous rotor optimization codes and the design process of the DTU 10MW RWT, development of a new more versatile software for rotor optimization was started.

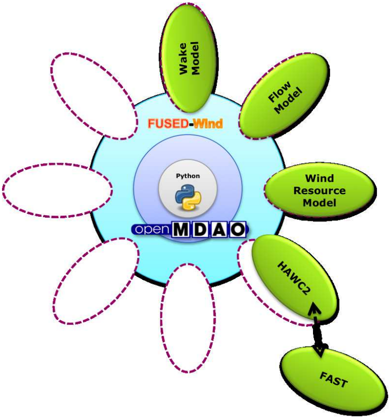
Requirements

- *Think beyond optimization*: A unified analysis tool can help break disciplinary barriers.
- *Simple interfaces*: We wanted to create simple to use interfaces to potentially very complex codes.
- *Changing workflows*: We wanted to be able to change around how codes are wired together to adapt to different usage scenarios.
- *User extensibility*: The user community should be able to extend the framework with their own tools.

FUSED-Wind - Framework for Unified Systems Engineering and Design of Wind Turbine Plants (fusedwind.org)

Collaboration with NREL

- NREL is working towards many of the same goals as we are, and also chose to use OpenMDAO.
- This has led to a close collaboration around a jointly developed open source framework called *FUSED-Wind*.
- The framework includes pre-defined *interfaces*, *workflows* and *I/O definitions* that enables easy swapping of codes into the same workflow.
- Each organisation will release separate software bundles that target specific usages, i.e. airfoil, turbine, and wind farm optimization.



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FUSED-Wind - Framework for Unified Systems Engineering and Design of Wind Turbine Plants (fusedwind.org)

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Versions

Development
0.1.dev Github

Stable
v0.1.0

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Overview

Framework for Unified Systems Engineering and Design of Wind Plants (FUSED-Wind) is a free open-source framework for multi-disciplinary optimisation and analysis (MDAO) of wind energy systems, developed jointly by the Wind Energy Department at the Technical University of Denmark (DTU Wind Energy) and the National Renewable Energy Laboratory (NREL). The framework is built as an extension to the NASA developed OpenMDAO, and defines key interfaces, methods and I/O variables necessary for wiring together different simulation codes in order to achieve a system level analysis capability of wind turbine plants with multiple levels of fidelity. NREL and DTU have developed independent interfaces to their respective simulation codes and cost models with the aim of offering an environment where these codes can be used interchangeably. The open source nature of the framework enables third parties to develop interfaces to their own tools, either replacing or extending those offered by DTU and NREL.

GitHub Repository

The project source code is hosted on https://github.com/FUSED-Wind. Along with the FUSED-Wind source code, you can find the code for the examples and tutorials accompanying the documentation on this site. On github.com you can also ask questions, report bugs and request features. For a better overview of all issues and the current progress of the project visit our Waffle page.

Contacts

If you want more information about the platform, please contact the following authors

DTU: Pierre-Elouan Réthoré, Frederik Zahle,

NREL: Katherine Dykes, Peter Graf, Andrew Ning

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FUSED-Wind - Framework for Unified Systems Engineering and Design of Wind Turbine Plants (fusedwind.org)

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- Tutorials
- Developer Guide
- Source Documentation

Tutorials

These tutorials cover example usage of fused_wind for simple wind turbine and plant analysis applications.

- Writing a FUSED-Wind Compatible Model
- Plant Cost and Financial Analysis Tutorials
  - Turbine Cost Models
  - Balance of Station Cost Models
  - Operational Expenditures Models
  - Finance Models
- Energy Production Tutorials
  - Tutorial for Basic_AEP
  - Tutorial for AEPMultipleWindRoses
- Run Batch Tutorials
  - Run Case Generator
  - Case Runner
- Turbine Tutorials
  - Airfoil and Blade Geometry Examples
  - Blade Structure Example
  - Aero-elastic Turbine Example
  - Coupled Structural Aero-elastic Turbine Example

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HawtOpt2: Aero-Servo-Elastic Optimization of Wind Turbines

Fully Coupled Aero-structural Optimization

- Simultaneous optimization of lofted blade shape and the composite structural design.
- Enables exploration of the many often conflicting objecting and constraints in a rotor design.
- Detailed tailoring of aerodynamic and structural properties.
- Constraints on specific fatigue damage loads.
- Placement of natural frequencies and damping ratios.

Software Design
Aero-Elastic Solver: HAWCStab2

- Structural model: geometrically non-linear Timoshenko finite beam element model.
- Aerodynamic model: unsteady BEM including effects of shed vorticity and dynamic stall and dynamic inflow.
- Analytic linearization around an aero-structural steady state ignoring gravitational forces.
- Fatigue damage calculated in frequency domain based on the linear model computed by HAWCStab2.

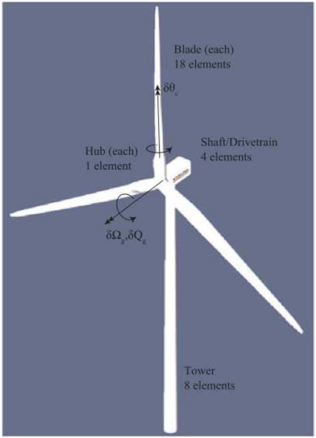
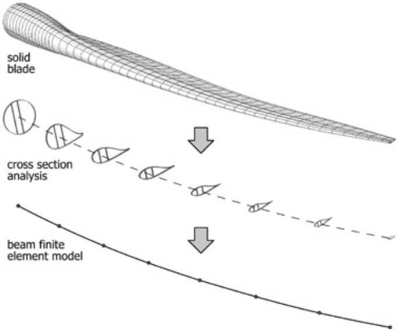
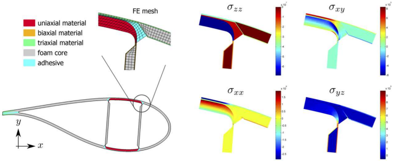


Image from: Sønderby and Hansen, Wind Energy, 2014

Structural Solver: BECAS (BEam Cross section Analysis Software)

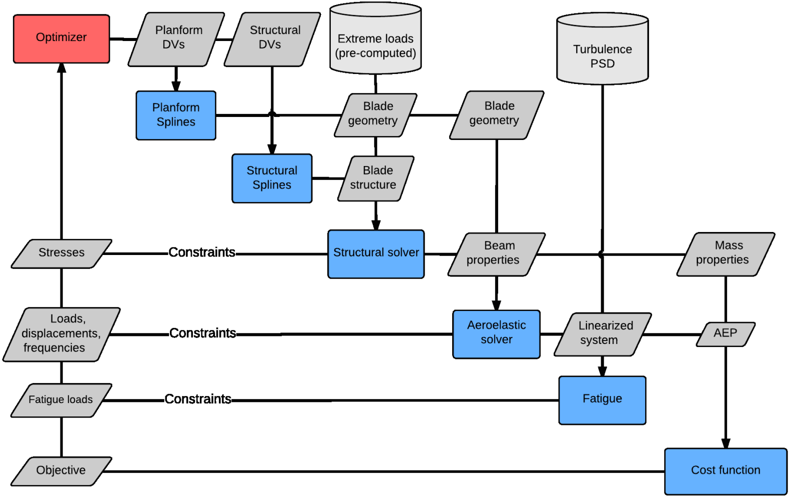
- Finite element based tool for analysis of the stiffness and mass properties of beam cross sections.
- Correctly predicts effects stemming from material anisotropy and inhomogeneity in sections of arbitrary geometry (e.g., all coupling terms).
- Detailed stress analysis based on extreme loads from a time-domain aeroelastic solver.



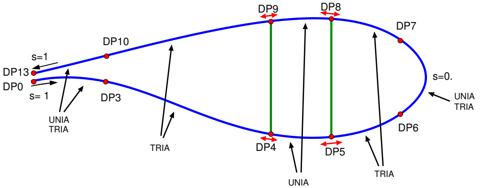


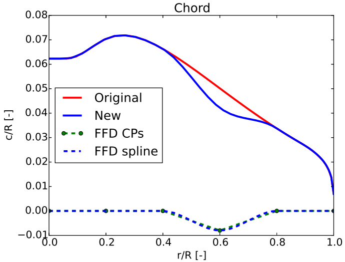
Software Design

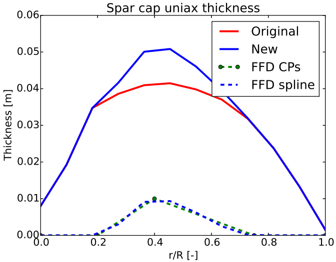
Optimizer Workflow Diagram



Free-form Deformation (FFD) Design Variable Splines







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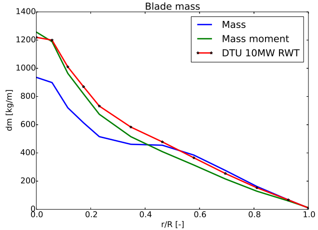
Case 1: Pure Structural Optimization with Fixed Outer Shape

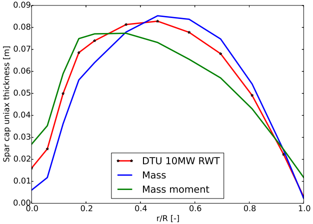
Minimise (Case 1a)	$-\frac{M_{blade-ref}}{M_{blade}}$
Minimise (Case 1b)	$-\frac{Mmom_{blade-ref}}{Mmom_{blade}}$
with respect to	$x = \{t_{mat}, DP_{caps}\}$ (47 dvs)
subject to	Constraints on: Tip deflection at rated power, Tip torsion at rated, Ultimate strength, Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$, $\frac{P_{mek}}{P_{mek-ref}} > 1.$ $\frac{T_{max}}{T_{max-ref}} < 1.$

- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

Case 1: Mass Distribution

- Minimization of either mass or mass moment results in drastically different designs.
- Mass minimization: 17% reduction in mass, 0.6% increase in mass moment,
- Mass moment minimization: 9% reduction in mass, 13% reduction in mass moment.
- Mass minimization tends to remove mass primarily from the inner 50% span.
- Mass moment minimization removes mass more evenly, which will contribute to a reduction in fatigue.





Case 2: Shape and structural Optimization for Mass and AEP

Minimise	$-\left(w_{pow} * \frac{AEP}{AEP_{ref}} + (1 - w_{pow}) * \frac{M_{blade-ref}}{M_{blade}}\right)$
For cases	w_{pow} = [0.8, 0.85, 0.9, 0.925, 0.95, 0.975]
with respect to	$x = \{c, \theta, t_{blade}, t_{mat}, DP_{caps}\}$ (56 dvs)
subject to	Constraints on: Tip deflection at rated power, Extreme wind tip deflection, Ultimate strength, Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$, $T_{rated} < T_{rated-ref}$, $T_{extreme} < T_{extreme-ref}$, Extreme blade flapwise load $<$ ref value Extreme blade edgewise load $<$ ref value

- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
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Case 2: Pareto Optimal Designs

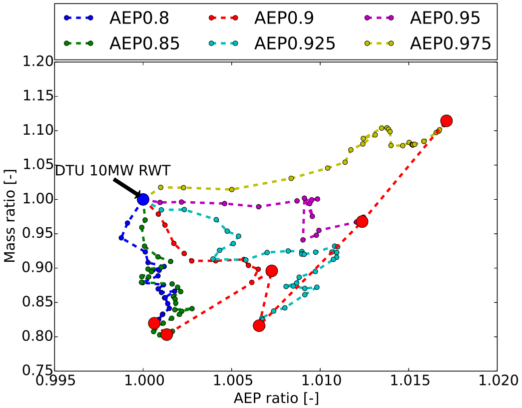

Figure: Pareto optimal designs for the massAEP cases.

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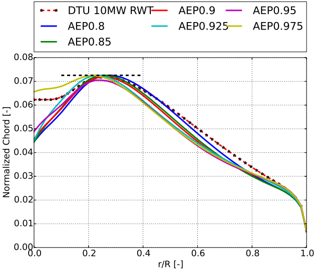
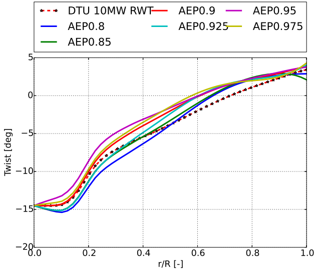
Case 2: Blade Planform

- All designs tend towards a more slender chord distribution, and a significant reduction in root diameter.
- Maximum chord constraint is active.





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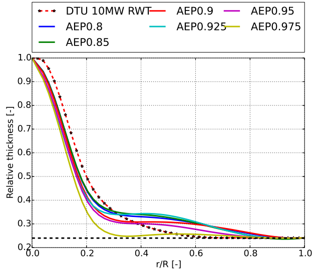
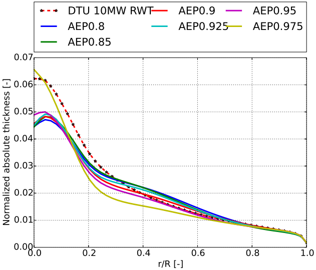
Case 2: Blade Planform

- All designs tend towards a more slender chord distribution, and a significant reduction in root diameter.
- Maximum chord constraint is active.
- Significant increases in relative thickness mid-span in particular for the mass-biased designs.
- Absolute thickness lower in root and higher midspan.





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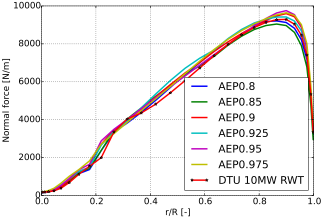
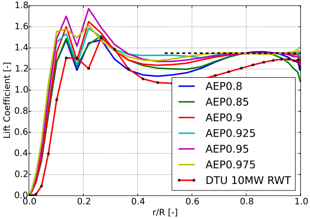
Case 2: Aerodynamic Performance at 10 m/s

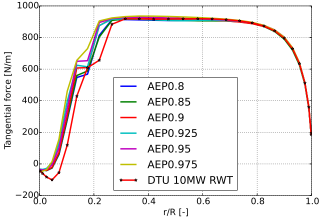
- Mass biased designs tend towards unloading the tip.
- Slender design requires higher operational lift coefficients
- $Cl - max$ constraint active for all designs.

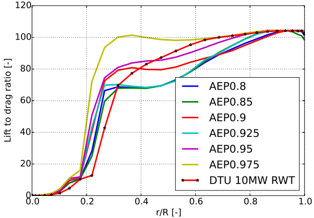




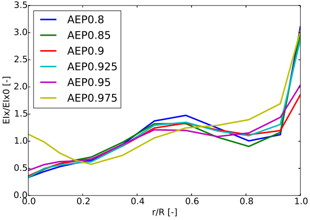
Case 2: Aerodynamic Performance at 10 m/s

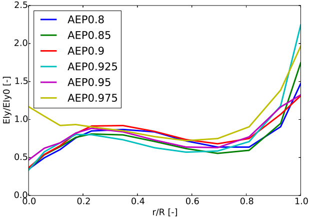
- Mass biased designs tend towards unloading the tip.
- Slender design requires higher operational lift coefficients
- $Cl - max$ constraint active for all designs.
- Increase in thickness compromises performance mid-span.
- Increase in performance on inner part of blade due to reduction in thickness.

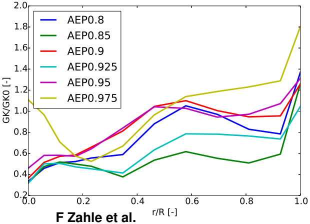


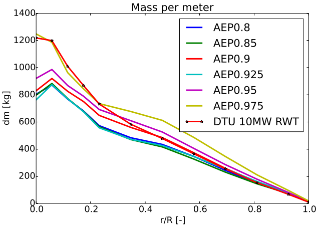


Case 2: Structural Characteristics









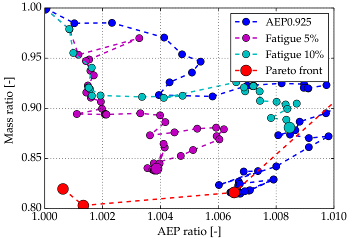
Case 3: Shape and structural Optimization with Fatigue Constraints

Minimise	$-\left(w_{pow} * \frac{AEP}{AEP_{ref}} + (1 - w_{pow}) * \frac{M_{blade-ref}}{M_{blade}}\right)$
with	$w_{pow} = 0.9$
with respect to	$x = \{c, \theta, t_{blade}, t_{mat}, DP_{caps}\}$ (56 dvs)
subject to	Constraints on: Tip deflection at rated power, Tip torsion at rated, Extreme wind tip deflection, Ultimate strength, Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$, $T_{rated} < T_{rated-ref}$, $T_{extreme} < T_{extreme-ref}$, Extreme blade flapwise load $<$ ref value Extreme blade edgewise load $<$ ref value Tower bottom long. fatigue $<$ [5%, 10%] Blade rotor speed fatigue $<$ ref value

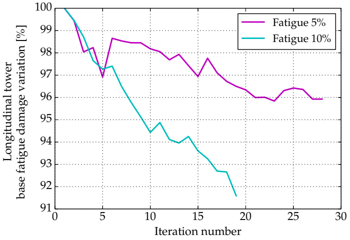
- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

Case 3: Pareto Front

- Fatigue constrained designs lie inside the pareto front of the massAEP designs.
- Both the 5% and 10% fatigue constraint almost met.
- Optimizations not fully converged.



a) AEP and blade mass in the Pareto front.



b) Tower base longitudinal bending moment fatigue damage variation.

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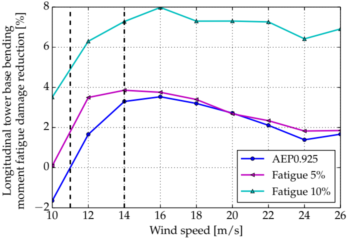
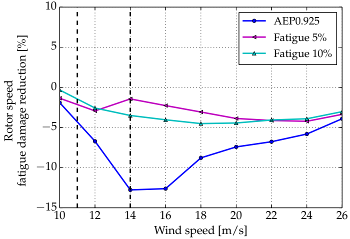
Case 3: Validation of Results With Time Domain Simulations

- Fatigue damage equivalent load reduction of tower base longitudinal bending moment and rotor speed with respect to the reference design.
- Values evaluated with nonlinear time domain simulations.
- Dashed vertical lines indicate the wind speed where the constraint is present in the optimization.





Case 4: Shape and structural Optimization with Frequency Constraint

Minimise $-\left(w_{pow} * \frac{AEP}{AEP_{ref}} + (1 - w_{pow}) * \frac{M_{blade-ref}}{M_{blade}}\right)$

with $w_{pow} = 0.9$

with respect to $x = \{c, \theta, t_{blade}, t_{mat}, DP_{caps}\}$ (56 dvs)

subject to Constraints on:
Tip deflection at rated power,
Tip torsion at rated,
Extreme wind tip deflection,
Ultimate strength,
Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$,
$T_{rated} < T_{rated-ref}$,
$T_{extreme} < T_{extreme-ref}$,
Extreme blade flapwise load $<$ ref value
Extreme blade edgewise load $<$ ref value
abs((Edgewise FW mode frequency)/6P) $>$ 7%
min(Edgewise BW mode damping) $>$ 1%

- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

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Results
Case 4: Pareto Front

- The frequency constrained design lies significantly inside the pareto front of the massAEP designs.

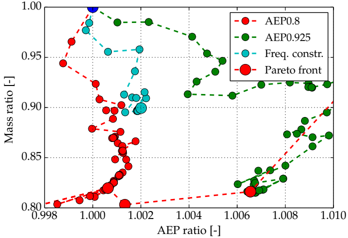

Figure: Iterations of Test case 4 optimizations.

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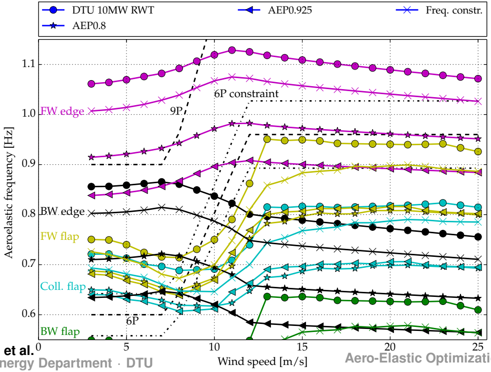
Case 4: Aeroelastic Frequencies

- All aeroelastic frequencies of the optimized designs are reduced.
- The FW edgewise mode of the AEP0.8 design overlaps the 6P frequency, while the AEP0.925 is sufficiently below.
- The frequency constrained design hits the upper frequency constraint at 25 m/s.



Conclusions

- OpenMDAO is used as the backbone for a new framework for multidisciplinary analysis and optimization of wind turbines.
- The HawtOpt2 framework is built around the state-of-the-art software developed by DTU Wind Energy.
- Multi-disciplinary trade-offs between mass reduction and AEP successfully captured by the fully coupled MDO approach,
- Significant reductions in mass and increase in AEP, depending on the weighting of the cost function.
- New frequency based model for fatigue showed promising results with up to 8% reduction in tower bottom longitudinal fatigue.
- Frequency placement was demonstrated, although the constraint formulation resulted in less improvements in the design than the unconstrained designs.

Conclusions

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