Optimal wind turbine aeroelastic rotor design with active flaps

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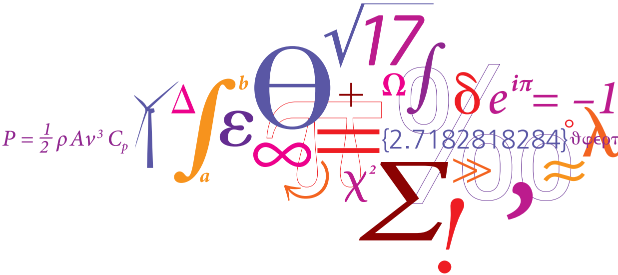


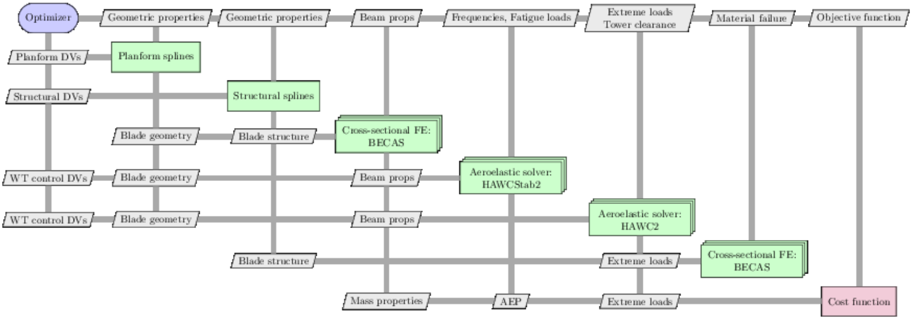
DTU Wind Energy
Department of Wind Energy

Outline

- The HAWTOpt2 Framework
- Optimization Results
- Closing statements

The HAWTOpt2 Work-flow

- IPOPT Optimization Algorithm
- Uses OpenMDAO for the glue code
- Cross Section Module (BECAS)
- Steady and Unsteady Aeroelastic Models (HAWC2)



Optimizer
Geometric properties
Geometric properties
Beam props
Frequencies, Fatigue loads
Extreme loads
Tower clearance
Material failure
Objective function

Planform DVs
Planform splines

Structural DVs
Structural splines

Blade geometry
Blade structure
Cross-sectional FE:
BECAS

WT control DVs
Blade geometry
Beam props
Aeroelastic solver:
HAWCStab2

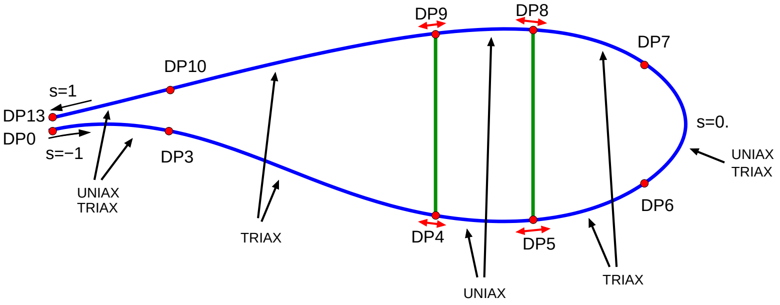
WT control DVs
Blade geometry
Beam props
Aeroelastic solver:
HAWC2

Blade structure
Extreme loads
Cross-sectional FE:
BECAS

Mass properties
AEP
Extreme loads
Cost function

Internal Structure Design Variables

- DP's control web positions and panel sizes
- Thickness design variables for main load carrying laminates
- Can have fiber angle design variables (not used here)



Optimization Formulation

- Maximize AEP
- Using planform and structural design variables
- Subject to geometric and load constraints

$$\begin{aligned}\underset{\mathbf{x}_p,\,\mathbf{x}_s,\,\mathbf{x}_{oper}}{\text{minimize}} \quad & f(\{\mathbf{x}_p,\ \mathbf{x}_s\ \mathbf{x}_{oper},\mathbf{p},w) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{x}_p) \leq \mathbf{0}, \\ & \mathbf{h}_\mathbf{g}(\mathbf{x}_s) \leq \mathbf{0}, \\ & \mathbf{h}_\mathbf{s}(\mathbf{x}_s) \leq \mathbf{0}, \\ & \mathbf{k}(\{\mathbf{x}_p,\ \mathbf{x}_s\}) \leq \mathbf{0}\end{aligned}$$

Where:

$$f(\{\mathbf{x}_p,\ \mathbf{x}_s,\ \mathbf{x}_{oper}\},\mathbf{p}) \quad = \quad \frac{AEP(\{\mathbf{0},\ \mathbf{0},\ \mathbf{0}\},\mathbf{p})}{AEP(\{\mathbf{x}_p,\ \mathbf{x}_s,\ \mathbf{x}_{oper}\},\mathbf{p})}$$

Design Variables

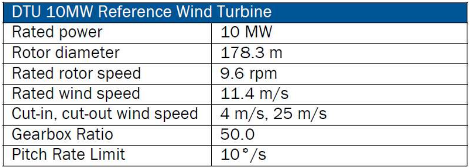
Parameter	# of DVs	**Comment**
Chord	6	-
Twist	5	Root twist fixed
Relative thickness	3	Root and tip relative thickness fixed
Blade prebend	4	-
Blade precone	1	-
Blade length	1	-
Tip-speed ratio	1	-
Trailing edge uniax	2	Pressure/suction side
Trailing edge triax	2	Pressure/suction side
Trailing panel triax	2	Pressure/suction side
Spar cap uniax	4	Pressure/suction side
Leading panel triax	2	Pressure/suction side
Leading edge uniax	2	Pressure/suction side
Leading edge triax	2	Pressure/suction side
DP4	5	Pressure side spar cap position/rear web attachment
DP5	5	Pressure side spar cap position/front web attachment
DP8	5	Suction side spar cap position/front web attachment
DP9	5	Suction side spar cap position/rear web attachment
Flap Angle	5	Flap angle at 5 wind speeds
Total	65	

Constraints

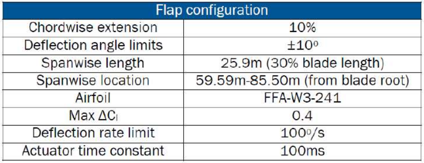
Constraint	Value	**Comment**
max(chord)	< 6.2 m	Maximum chord limited for transport.
max(prebend)	< 6.2 m	Maximum prebend limited for transport.
max(rotor cone angle)	> -5 deg	-
min(relative thickness)	> 0.24	Same airfoil series as used on the DTU 10MW RWT.
min(material thickness)	> 0.0	Ensure FFD splines do not produce negative thickness.
$t/w_{sparcap}$	> 0.08	Basic constraint to avoid spar cap buckling.
min(tip tower distance)	$>$ ref value	DLC1.3 operational tip deflection cannot exceed that of the DTU 10MW RWT.
Blade root flapwise moments (MxBR)	$<$ ref value	DLB loads cannot exceed starting point.
Blade root edgewise moments (MyBR)	$<$ ref value	DLB loads cannot exceed starting point.
Tower bottom fore-aft moments (MxTB)	$<$ ref value	DLB loads cannot exceed that starting point.
Rotor torque	$<$ ref value	Ensure that the rotational speed is high enough below rated to not exceed generator maximum torque.
Blade mass	$<$ 1.01 * ref value	Limit increase in blade mass to maintain equivalent production costs.
Blade mass moment	$<$ 1.01 * ref value	Limit increase in blade mass moment to minimize edgewise fatigue.
Lift coefficient @ $r/R = [0.5 - 1.]$	< 1.35	Limit operational lift coefficient to avoid stall for turbulent inflow conditions.
Ultimate strain criteria	< 1.0	Aggregated material failure in each section for 12 load cases.
Flap Angle	$-15.0 \geq \beta \geq 15.0$	Flap angle stays within 15 degree bounds

Flap Configuration

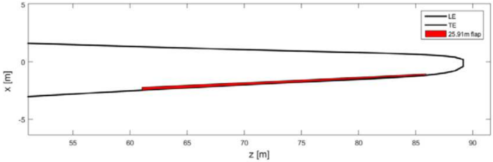
- Flap only deflected in below rated conditions
- Flap operates in a quasi-steady mode



DTU 10MW Reference Wind Turbine	
Rated power	10 MW
Rotor diameter	178.3 m
Rated rotor speed	9.6 rpm
Rated wind speed	11.4 m/s
Cut-in, cut-out wind speed	4 m/s, 25 m/s
Gearbox Ratio	50.0
Pitch Rate Limit	10°/s

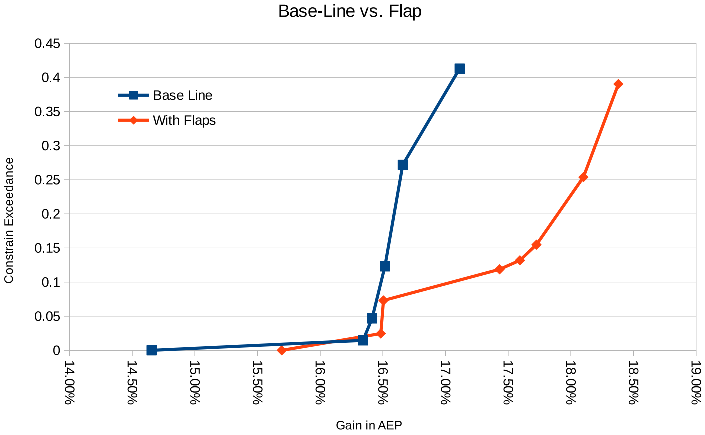


Flap configuration	
Chordwise extension	10%
Deflection angle limits	±10°
Spanwise length	25.9m (30% blade length)
Spanwise location	59.59m-85.50m (from blade root)
Airfoil	FFA-W3-241
Max ΔC_l	0.4
Deflection rate limit	100°/s
Actuator time constant	100ms



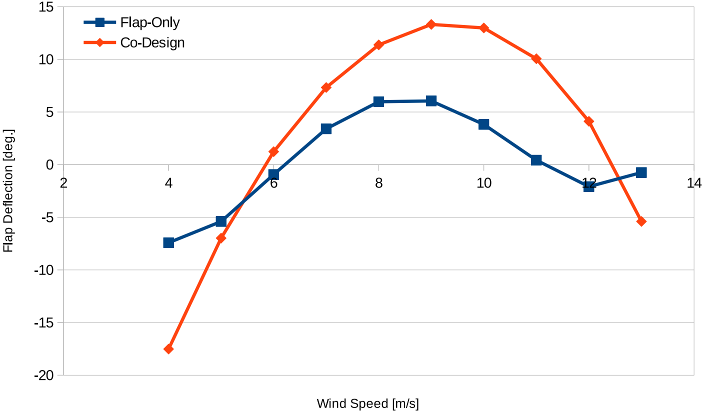
Optimal Solution

- Blade optimization not totally converged
- Pareto front shows consistent 1% improvement in AEP
- Add-on flap only gives 0.51% improvement



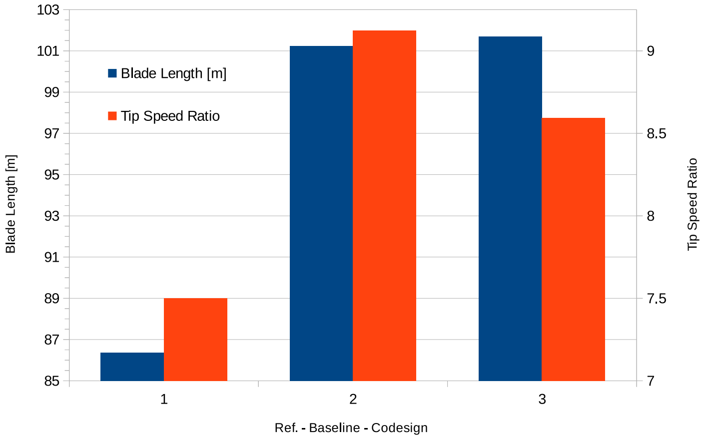
Flap Deflection

- Both start at negative angles, increase the decrease with increasing wind speed
- Co-design allowed more aggressive utilization of the flaps



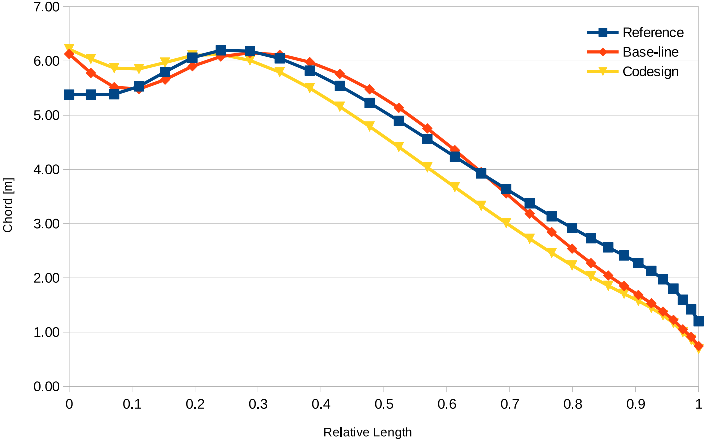
Length and Speed

- Co-design produced a 0.5% longer blade
- Co-design produced a slower rotor



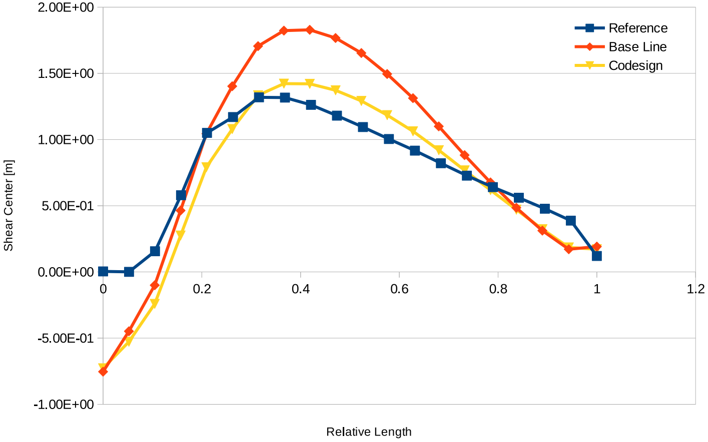
Blade Chord

- Baseline moves solidity from the tip to the root
- Co-design has overall decreased solidity but similar distribution



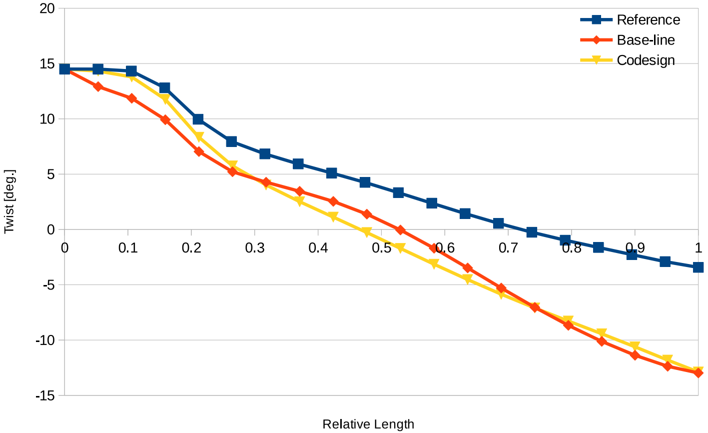
Shear Center

- Forward shifted shear center introduces shear-twist coupling to reduce loads
- Co-design relies less on passive load alleviation



Blade Twist

- Overall flaps had little impact on the optimal twist distribution

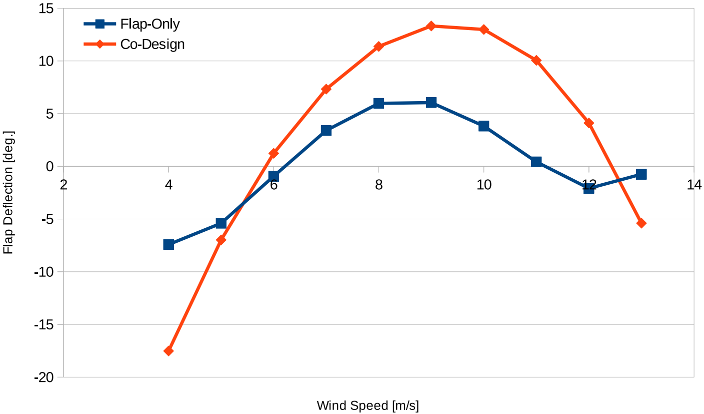


Many Design Parameters Unaffected

- Flaps had little impact on the following optimal design variables
    - Prebend
    - Relative thickness
    - Mass
    - Flapwise stiffness
    - Torsional stiffness

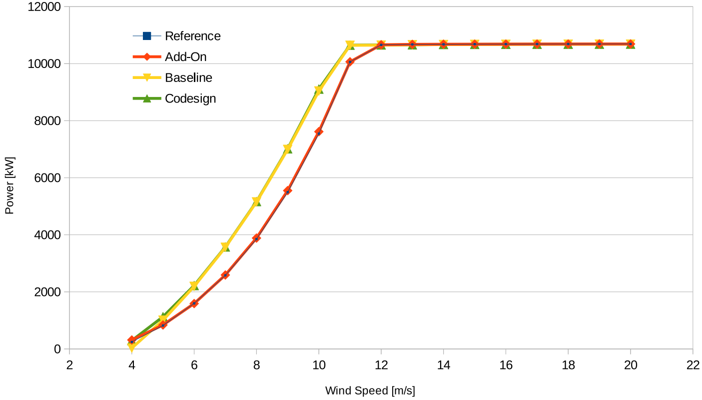
Flap Deflection

- Both start at negative angles, increase the decrease with increasing wind speed
- Co-design allowed more aggressive utilization of the flaps



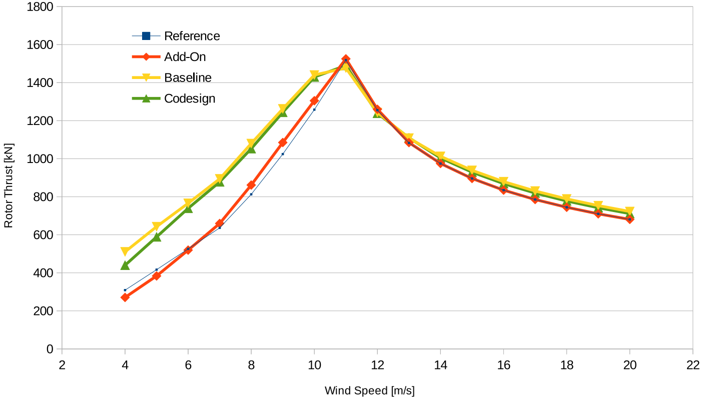
Power

- Flaps improve power at low wind speeds, otherwise small



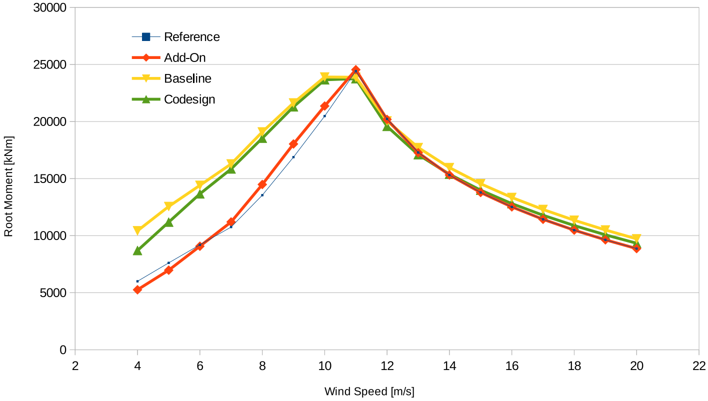
Thrust

- As an add-on, peak thrust is the same, mixed otherwise
- Flaps reduce the thrust in the co-design



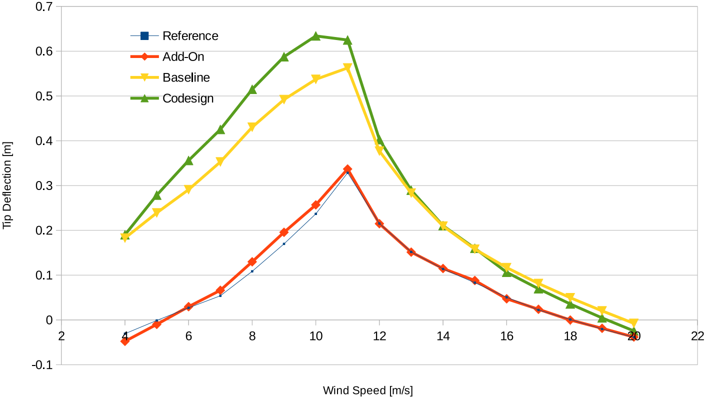
Bending Moment

- As an add-on, peak moment is the same, mixed otherwise
- Flaps reduce the moment in the co-design



Tip Deflection

- As an add-on, little change
- Co-design: Higher deflection, then flap is used for peak-shaving



Conclusions

- Add-on solution will give 0.5% improvement in AEP
- Co-design increases the AEP by 1%
    - Load control allows lower solidity (lower bound on loading)
    - Flaps used to increase loading where there is capacity
- Optimal load alleviation is quadratic with increasing wind speed
    - Active strategies are better than passive strategies
    - Co-design shows that only modest passive load alleviation is utilized
- Co-design has improved power, reduced loads and peak shaving capabilities
    - Flaps increase the power at low wind speeds
    - Flaps reduce the thrust and bending moments in co-design
    - Flaps increase the tip deflection, but attenuate at peak loading

Thank-you for your interest

Comments or Questions?