Multipoint high-fidelity CFD-based aerodynamic shape optimization of a 10 MW wind turbine

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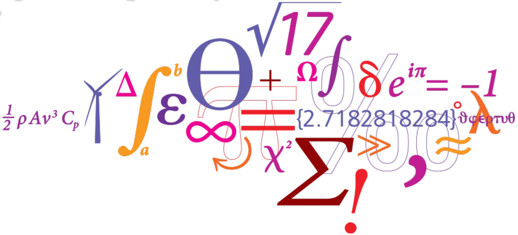

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Motivation and literature overview

Motivation

- To use CFD-based shape optimization early in the design process
- Gradients from Adjoint solvers does not depend on number of design variables
- To compare BEM and CFD on identical case studies

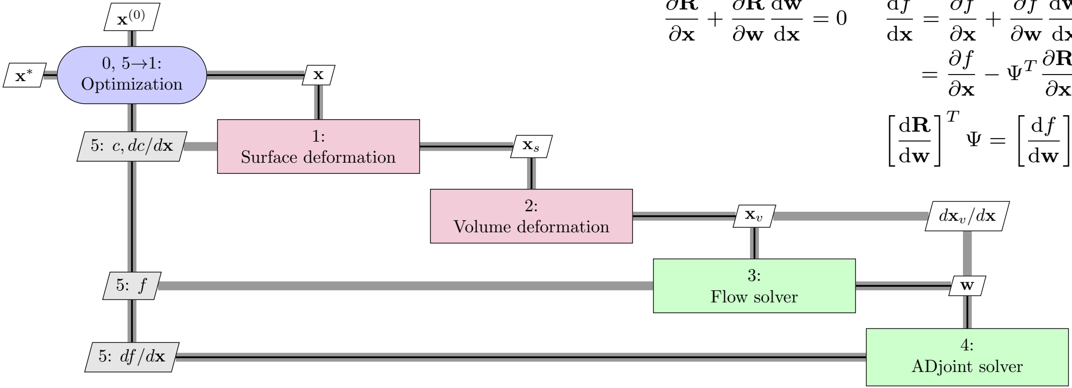
Table: Overview of related 3D works using the adjoint method.

Author	Year	Adjoint	Dim	Mesh size	variables	Iterations
Economon et al.	2013	Continuous	3D	$7.90 \cdot 10^6$	84	3
Vorspel et al.	2016	Continuous	3D	$2.4 \cdot 10^6$	-	< 8
Dhert et al.	2017	Discrete	3D	$2.60 \cdot 10^6$	1-252	≤ 23
Vorspel et al.	2018	Continuous	3D	$5.20 \cdot 10^6$	≤ 9	< 8
Tsiakas et al.	2018	Continuous	3D	$2.50 \cdot 10^6$	135	10
Madsen et al. (present work)	2018	Discrete	3D	$14.16 \cdot 10^6$	1-154	≤ 200

Please note:

- high-fidelity optimization still a rare commodity - (almost) all previous work is on NREL VI

Tool chain



State equation

$R(x, w) = 0$

$$\frac{\partial \mathbf{R}}{\partial \mathbf{x}} + \frac{\partial \mathbf{R}}{\partial \mathbf{w}} \frac{\mathrm{d}\mathbf{w}}{\mathrm{d}\mathbf{x}} = 0$$

Total derivative

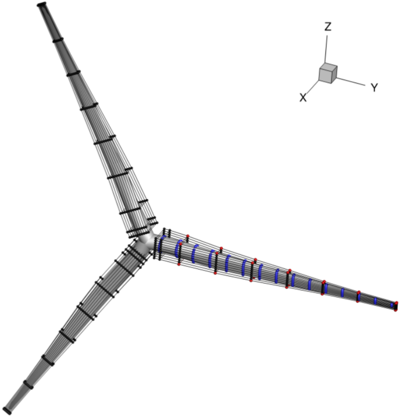
$$\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}} = \frac{\partial f}{\partial \mathbf{x}} + \frac{\partial f}{\partial \mathbf{w}} \frac{\mathrm{d}\mathbf{w}}{\mathrm{d}\mathbf{x}} = \frac{\partial f}{\partial \mathbf{x}} - \Psi^T \frac{\partial \mathbf{R}}{\partial \mathbf{x}}$$

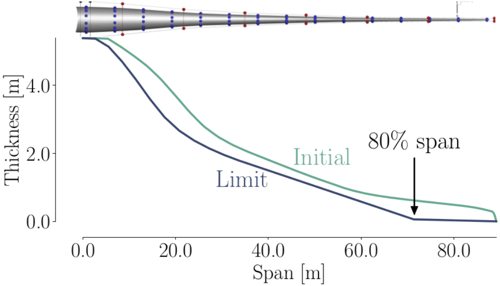
$$\left[\frac{\mathrm{d}\mathbf{R}}{\mathrm{d}\mathbf{w}}\right]^T \Psi = \left[\frac{\mathrm{d}f}{\mathrm{d}\mathbf{w}}\right]^T$$

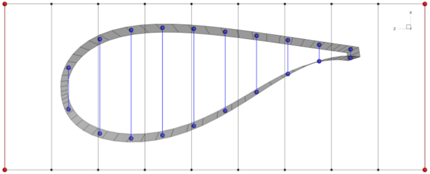
- Overview of MDOLab's optimization framework at University of Michigan.

Setup and design optimization problem

- Up to 154 design variables: Pitch, twist, chord and shape
- RANS steady state model







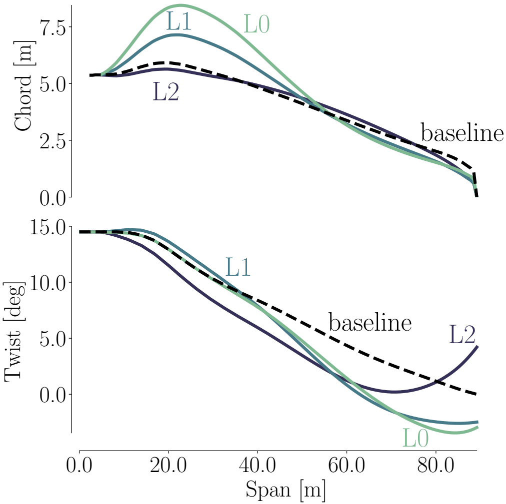
Design optimization problem

$$
\begin{array}{ll}
\underset{x}{\text{maximize}} & \mathrm{AEP}(x) \\
\text{with respect to} & \text{Chord}_i,\ i = 1, \ldots, (\text{n} - 2) \\
 & \text{Twist}_i,\ i = 1, \ldots, (\text{n} - 2) \\
 & \text{Shape}_i,\ i = 1, \ldots, \text{l} \cdot (\text{n} - 2) \\
\text{subject to} & \mathrm{Thrust}(x) \leq 1.14 \cdot \mathrm{Thrust}(x_0) \\
 & \mathrm{M}_b(x) \leq 1.11 \cdot \mathrm{M}_b(x_0) \\
 & \mathrm{Thickness}(x) \geq \mathrm{Thickness}_{IEA\ Task\ 37\ limit}.
\end{array}
$$

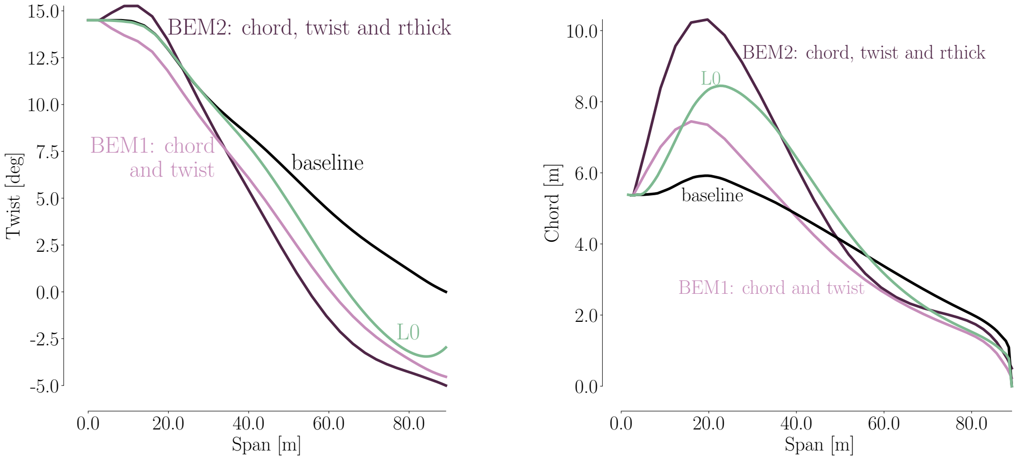
Planform optimization

$$
\begin{aligned}
\underset{x}{\text{maximize}} \quad & \text{Torque}(x) \\
\text{with respect to} \quad & \text{Pitch}, \\
& \text{Twist}_i,\ i = 1, \dots, 7, \\
& \text{Chord}_i,\ i = 1, \dots, 7, \\
& \text{Shape}_i,\ i = 1, \dots, l \cdot 420. \\
\text{subject to} \quad & \text{Thrust}(x) \leq 1.14 \cdot \text{Thrust}(x_0), \\
& \text{M}_b(x) \leq 1.11 \cdot M_b(x_0), \\
& \text{Thickness}(x) \geq \text{limit}_{IEA}.
\end{aligned}
$$

$C_P = 1.04, 0.62$ and 0.48 for mesh level L2, L1 and L0.



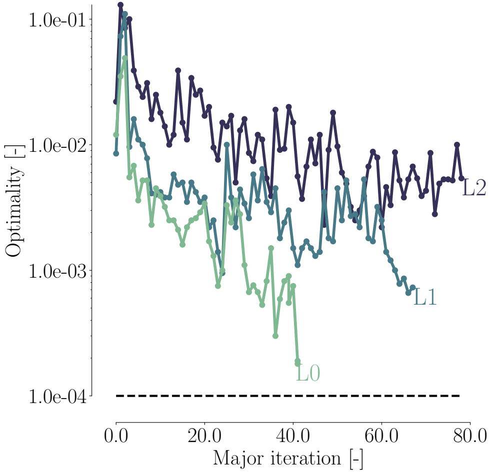
Comparison to BEM

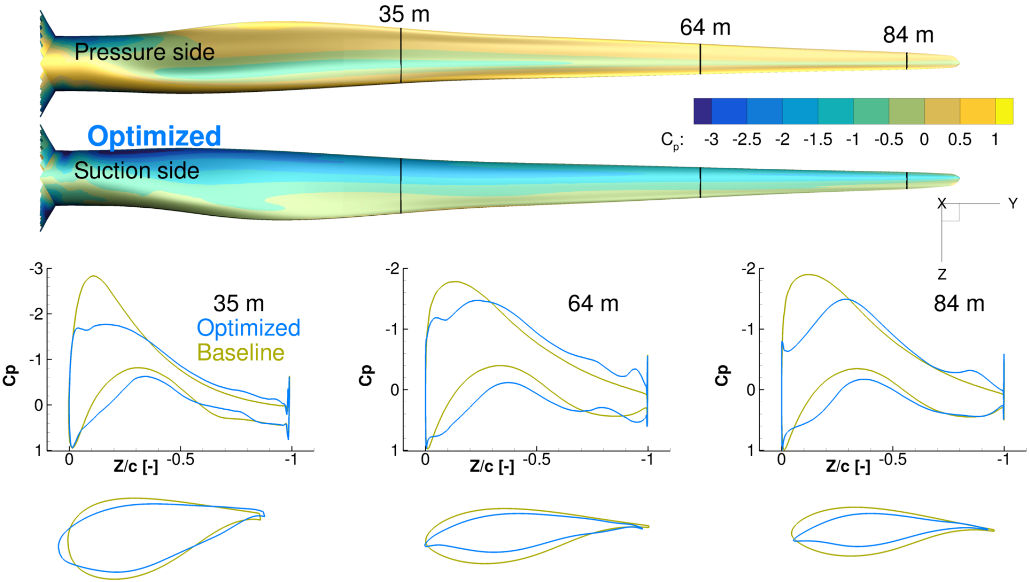


Shape optimization

$$
\begin{array}{ll}
\underset{x}{\text{maximize}} & \text{Torque}(x) \\
\text{with respect to} & \text{Pitch}, \\
 & \text{Twist}_i,\ i = 1, \ldots, 7, \\
 & \text{Chord}_i,\ i = 1, \ldots, 7, \\
 & \text{Shape}_i,\ i = 1, \ldots, \text{l} \cdot 140. \\
\text{subject to} & \text{Thrust}(x) \leq 1.14 \cdot \text{Thrust}(x_0), \\
 & \text{M}_b(x) \leq 1.11 \cdot M_b(x_0), \\
 & \text{Thickness}(x) \geq \text{limit}_{IEA}.
\end{array}
$$

In total 154 design variables





- Problematic leading edge shape for single point shape optimization

Overview of results from planform and single point

Table: A comparison to BEM results from IEA Task 37.

Mesh level	present work			IEA Task 37	
	Torque(x^0) $[Nm]$	Torque(x^*) $[Nm]$	Improvement	BEM1 Improvement	BEM2 Improvement
L 0: $14.155 \cdot 10^6$ $cells$	$4.88 \cdot 10^6$	$5.42 \cdot 10^6$	11.07%		
L 1: $1.769 \cdot 10^6$ $cells$	$6.12 \cdot 10^6$	$6.88 \cdot 10^6$	12.42%	8.06%	22.46%
L 2: $0.221 \cdot 10^6$ $cells$	$10.40 \cdot 10^6$	$11.57 \cdot 10^6$	11.25%		

Table: Overview of single point optimization results.

Mesh level	Single point optimization †		
	Torque(x^0) $[Nm]$	Torque(x^*) $[Nm]$	Improvement
L 0: $14.155 \cdot 10^6$ cells	$4.88 \cdot 10^6$	$5.65 \cdot 10^6$	15.78%
L 1: $1.769 \cdot 10^6$ cells	$6.12 \cdot 10^6$	$7.37 \cdot 10^6$	20.10%
L 2: $0.221 \cdot 10^6$ cells	$10.40 \cdot 10^6$	$12.70 \cdot 10^6$	22.11%

Multipoint shape optimizations

We can improve the leading edge shape by:

- Taking more AoAs into account:

- Adding geometrical leading edge constraints:

Conclusion

- It is feasible to use CFD earlier in the design process
- Constraints on flapwise bending-moment and geometry (LE) are a must
- Optimization should be multipoint and on sufficient mesh resolution

Future work

- Load envelope is a challenge
- Add structural discipline
- Transient simulations

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Abstract. The wind energy industry relies heavily on CFD to analyze new turbine designs. To utilize CFD further upstream the design process where lower fidelity methods such as BEM are more common, requires the development of new tools.

Thank you for your time

Questions ?

Literature overview

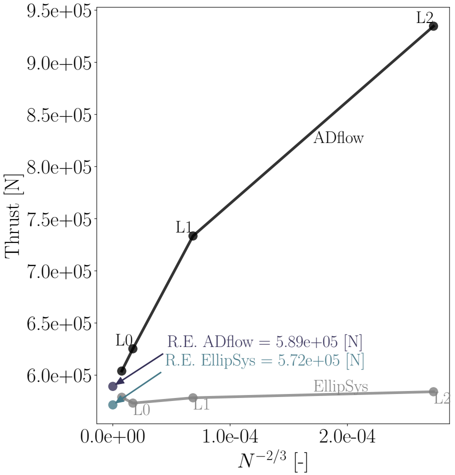
Table: Overview of related works using the adjoint method.

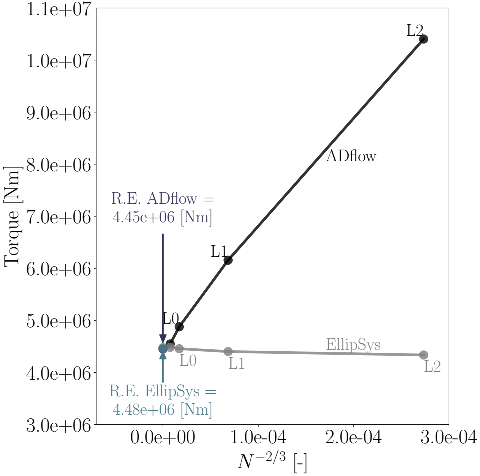
Author	Year	Adjoint	Dim	Mesh size	variables	Iterations
Ritlop and Nadarajah	2009	Discrete	2D	$0.32 \cdot 10^5$	385	≤ 200
Khayatzadeh and Nadarajah	2011	Discrete	2D	$1.31 \cdot 10^5$	385	-
Schramm et al.	2014	Continuous	2D	$55.00 \cdot 10^3$	720	-
Schramm et al.	2016	Continuous	2D	-	480	-
Barrett and Ning	2016	Continuous	2D	$14.00 \cdot 10^3$	≤ 22	-
Schramm et al.	2018	Continuous	2D	$2.08 \cdot 10^5$	≤ 50	≤ 30
Barrett and Ning	2018	Continuous	2D	$14.34 \cdot 10^3$	≤ 68	-
Economon et al.	2013	Continuous	2D	$32.0 \cdot 10^3$	50	10
			3D	$7.90 \cdot 10^6$	84	3
Vorspel et al.	2016	Continuous	2D	-	2	30
			3D	$2.4 \cdot 10^6$	-	< 8
Dhert et al.	2017	Discrete	3D	$2.60 \cdot 10^6$	1-252	≤ 23
Vorspel et al.	2018	Continuous	3D	† $5.20 \cdot 10^6$	≤ 9	< 8
Tsiakas et al.	2018	Continuous	3D	§ $2.50 \cdot 10^6$	135	10
Madsen et al. (present work)	2018	Discrete	3D	$14.16 \cdot 10^6$	1-154	≤ 200

† Symmetric BCs effectively doubling the grid resolution.

§ Tsiakas2018 only give the number of mesh nodes.

Analysis: Mesh convergence





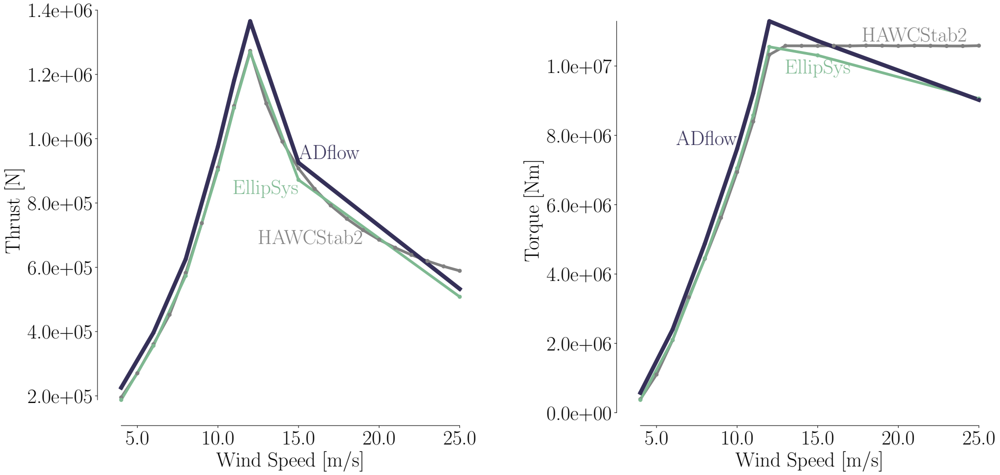
Analysis: Mesh convergence

Table: Mesh convergence study for the compressible solver ADflow and the incompressible solver EllipSys3D.

	ADflow				EllipSys3D			
Mesh level	Thrust	error	Torque	error	Thrust	error	Torque	error
L-1: 47.776	603	2.4 %	4.547	2.2 %	577	0.9 %	4.471	0.2 %
L 0: 14.155	625	6.1 %	4.877	9.6 %	573	0.2 %	4.457	0.5 %
L 1: 1.769	733	24.4 %	6.156	38.3 %	578	1.0 %	4.402	1.7 %
L 2: 0.221	934	58.6 %	10.403	134.5 %	584	2.1 %	4.336	3.2 %

Mesh level: $\cdot 10^6$ [cells], Torque: $\cdot 10^6$ [Nm], thrust: $\cdot 10^3$ [N]

Analysis: Integrated loads



Pitch optimization