NREL
Transforming ENERGY

# Design space exploration for novel reduced-vortex turbine rotors using free vortex wake methods

Cory Frontin, P. Bortolotti, E. Branlard,
L. Martínez, G. Vijayakumar, & G. Barter

NAWEA/WindTech
30 October 2023

# Wind turbine power optimization (status quo)

$$\text{maximize}_{\{c_i,\theta_i\}_{i=1}^N} \; C_P$$

$$\text{subject to E.o.M.}$$

approximated by

$$\text{maximize}_{\{c_i,\theta_i\}_{i=1}^N} \; C_P$$

$$\text{subject to BEM eqns.}$$

a simplified yet common blade design problem:
- maximize power output
- changing chord and twist

given a geometry, power is approximated by the BEM equations

power-maximizing chord and lift distributions determined algorithmically (using dozens of solutions of BEM eqn.)

# Blade design methods *mimic* reality

*BEM-based design*

basic aerodynamic model
⇐ airfoil lift and drag polars

neglect all interactions between vortices and blade sections

tip and wake rotation effects
⇐ simple engineering models

intuitive modeling assumptions
⇐ a different era of computing

*Idealized design*

optimization across full spectrum of aerodynamic behavior

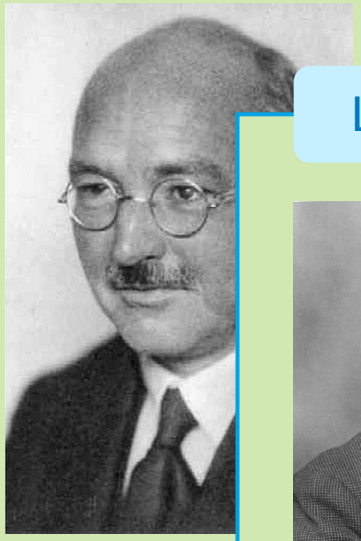
full consideration of coupling
- spanwise vortex distribution
- tip and wake treatment
- radial/spanwise flow/interactions

resolve the effects of all relevant features of turbine flow in space and time

# All simulation methods mimic reality

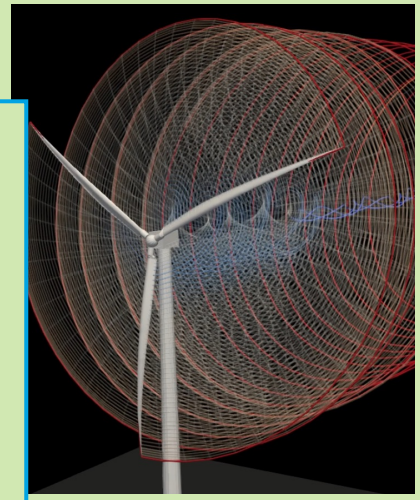
## … at different levels of cost and fidelity

BEM

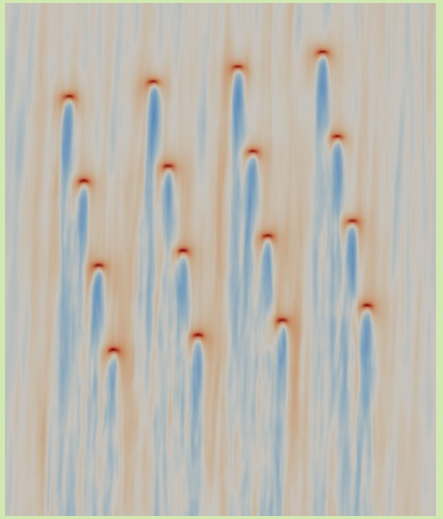


Lifting Lines

Vortex Methods



Actuator Modeled CFD



Blade-resolving CFD

increasing cost, increasing fidelity

# Can physical wind turbines be designed to generate more power than BEM designs?

Madsen, et. al., 2022:

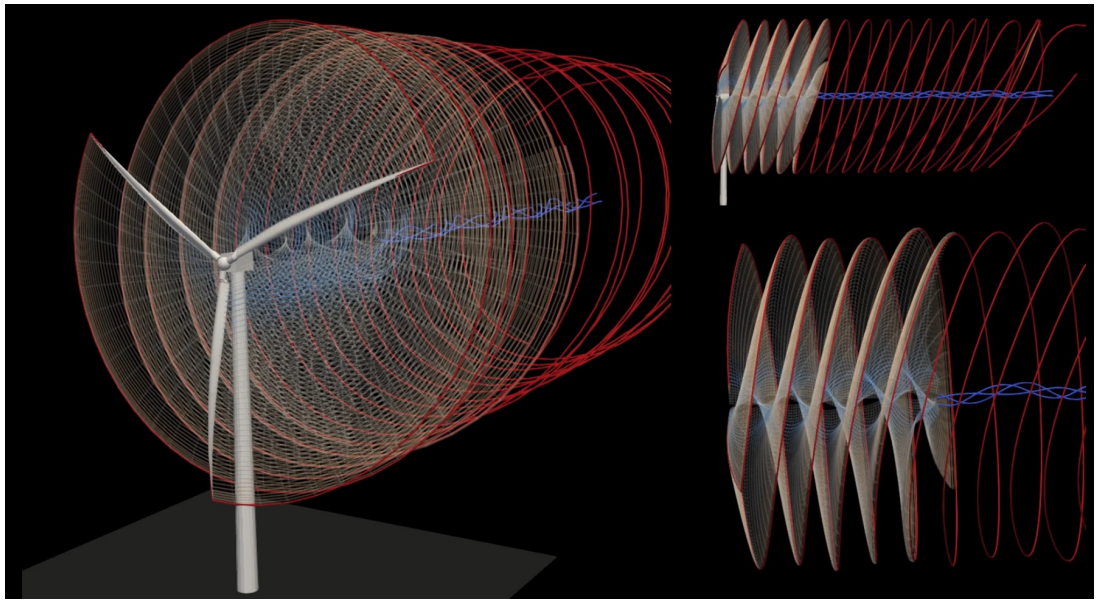
- post-hoc winglet modification for turbine blades
- CFD-based optimization
  - maximize $C_P$ without increasing thrust
  - 1-2% improvement in $C_P$
  - twist, chord, and tip geometry variation

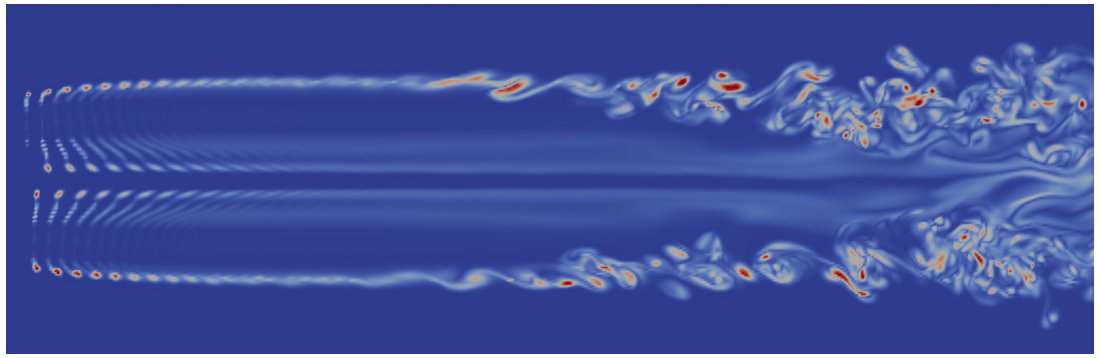
Barlas, et. al., (2021 & 2022):

- experimental studies of winglet modification
- multi-fidelity simulation comparison against experimental results
- broad agreement
  - all methods include some non-representation of physical phenomena

# Can we create designs using mid-fidelity methods that out-perform BEM-based designs?

# OLAF: NREL's Free Vortex Wake Solver

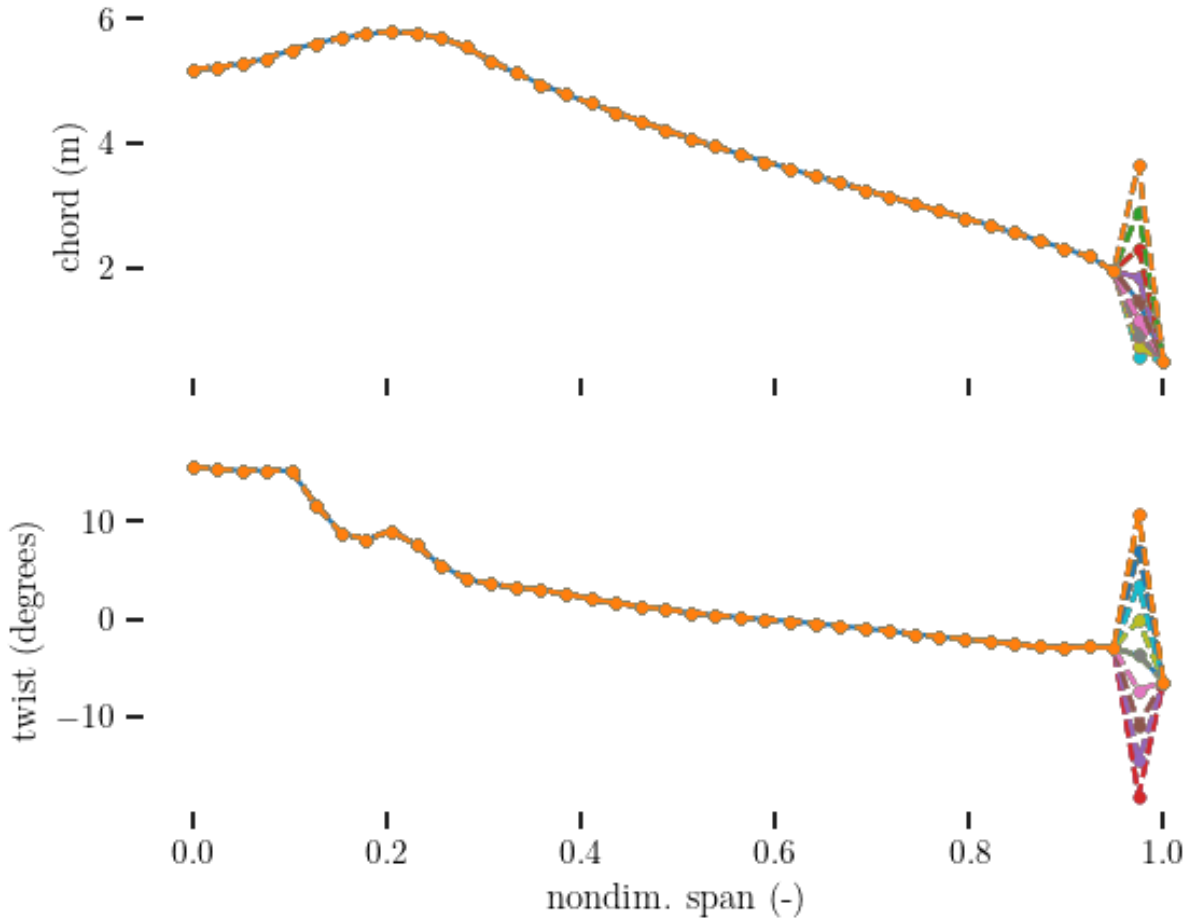




OLAF:

- medium-fidelity aero discretization
- discretizes vortices allowing convection, stretching, dissipation, etc.
- under the hood:
  - blades: lifting-line method
  - near wake: vortex lattice
  - far wake: convecting Lagrangian filaments for root/tip vortices

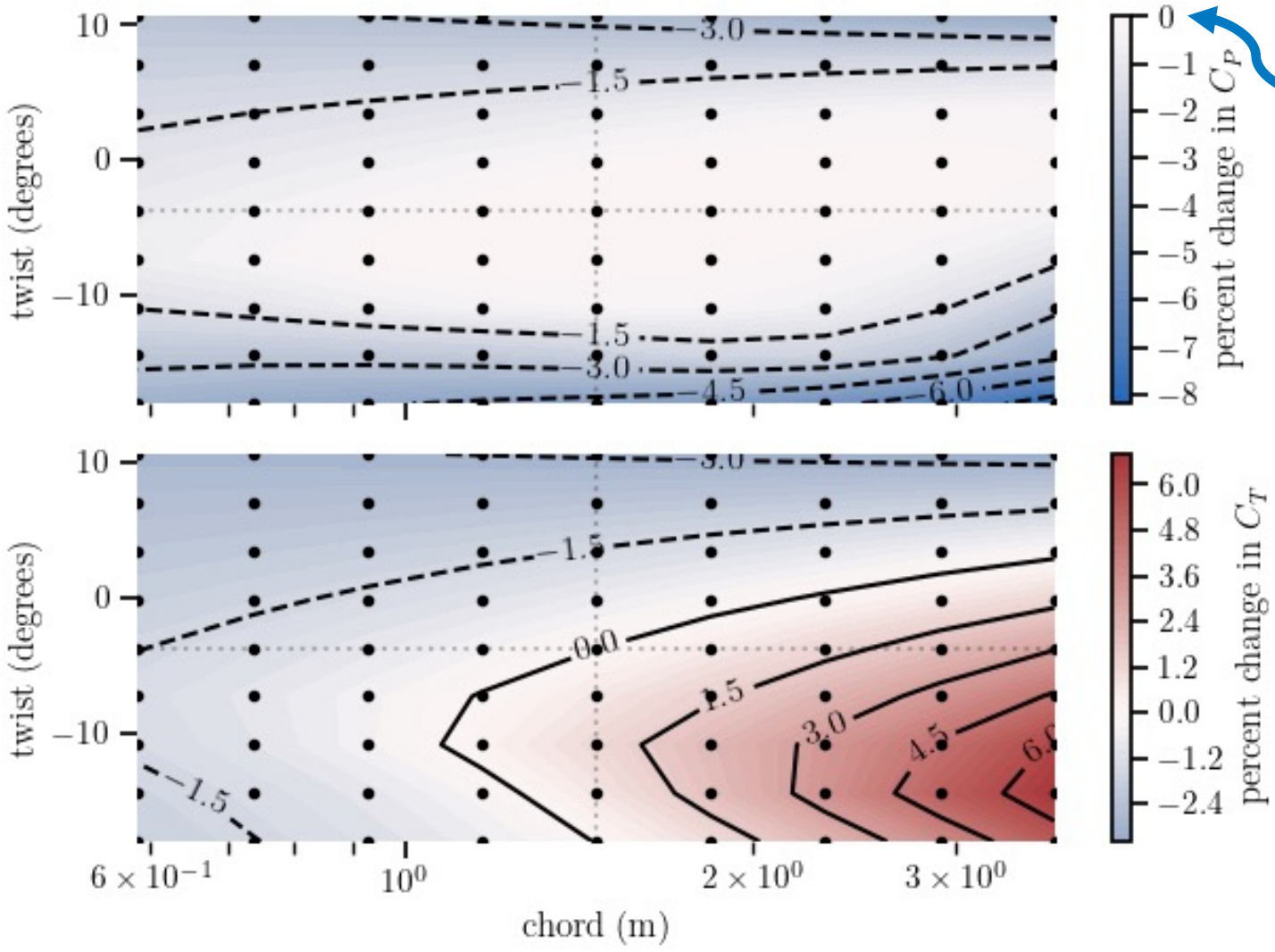
# Design of experiments: perturbations




make perturbations

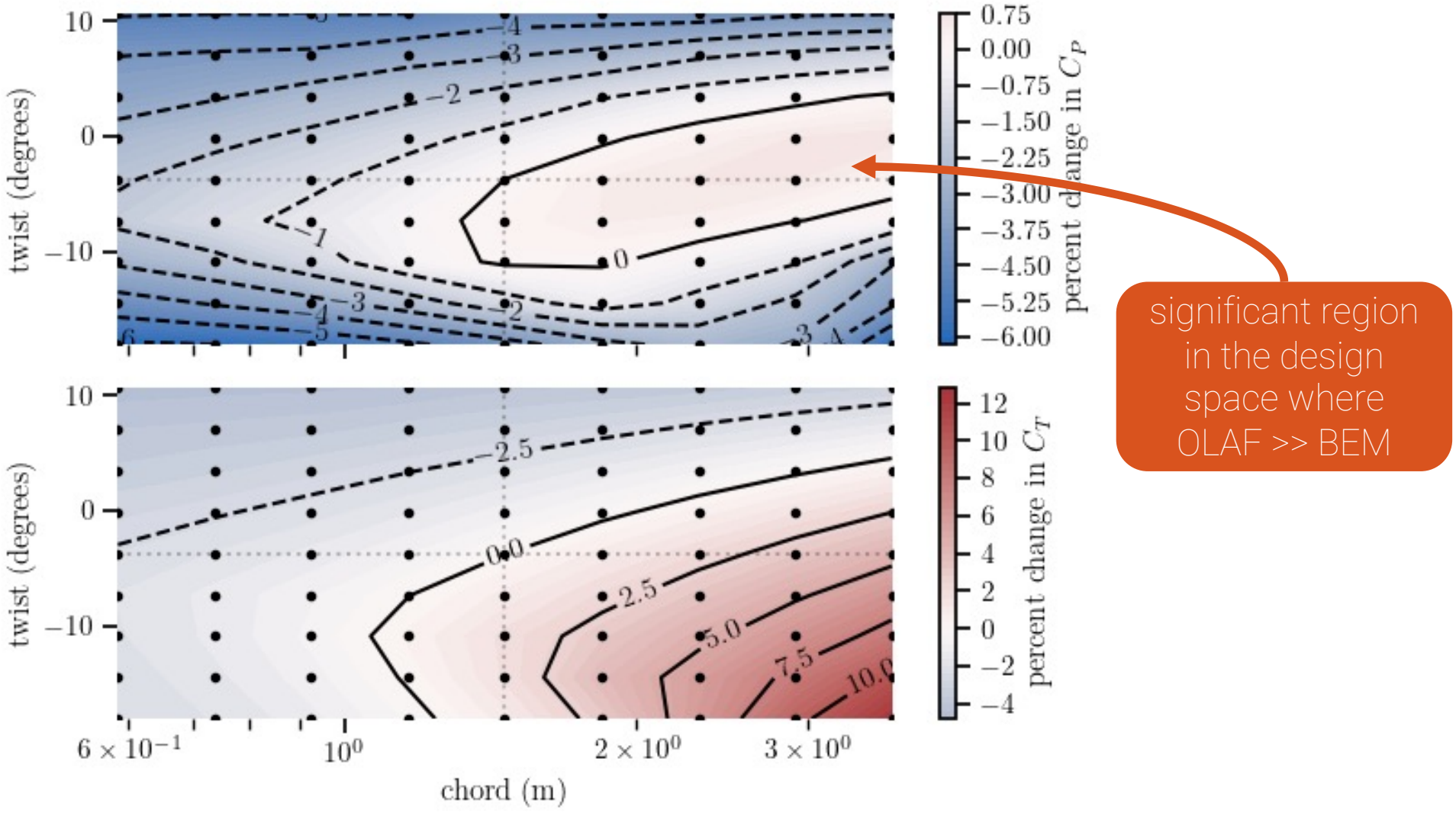
- chord & twist
- 9x9 grid
- at each point: evaluate aero performance
  - BEM
  - OLAF (FVW) w/ 150 pts. (converged)

# Design of experiments: BEM




across the response surface, power is nowhere improved

# Design of experiments: OLAF




significant region in the design space where OLAF >> BEM

# Can we create optimal designs using mid-fidelity methods in the design loop?

# Wind turbine power optimization (proposed)

$$\text{maximize}_{\{c_i,\theta_i\}_{i=1}^{N}} \; C_P$$

$$\text{subject to E.o.M.}$$

approximated by

$$\text{maximize}_{\{c_i,\theta_i\}_{i=1}^{N}} \; C_P$$

$$\text{subject to F.V.W. E.o.M.}$$

rather than BEM, use OLAF FVW to design the rotor blade

some subtle changes:

- interactions between blade sections introduced
  - formerly:
    $\Delta C_P \Leftarrow \Delta(\text{flow})_j \Leftarrow \Delta\{c_j, \theta_j\}$
  - now:
    $\Delta C_P \Leftarrow \{\Delta(\text{flow})_j\}_{j=1}^{N} \Leftarrow \Delta\{c_j, \theta_j\}_{j=1}^{N}$
- optimization more complex
  - global ~~local~~ subproblem

# Wind turbine power optimization w/ SNOPT

$$\text{maximize}_{\{c_i,\theta_i\}_{i=1}^{N}} \; C_P$$

$$\text{subject to E.o.M.}$$

approximated by

$$\text{maximize}_{\{c_i,\theta_i\}_{i=1}^{N}} \; C_P$$

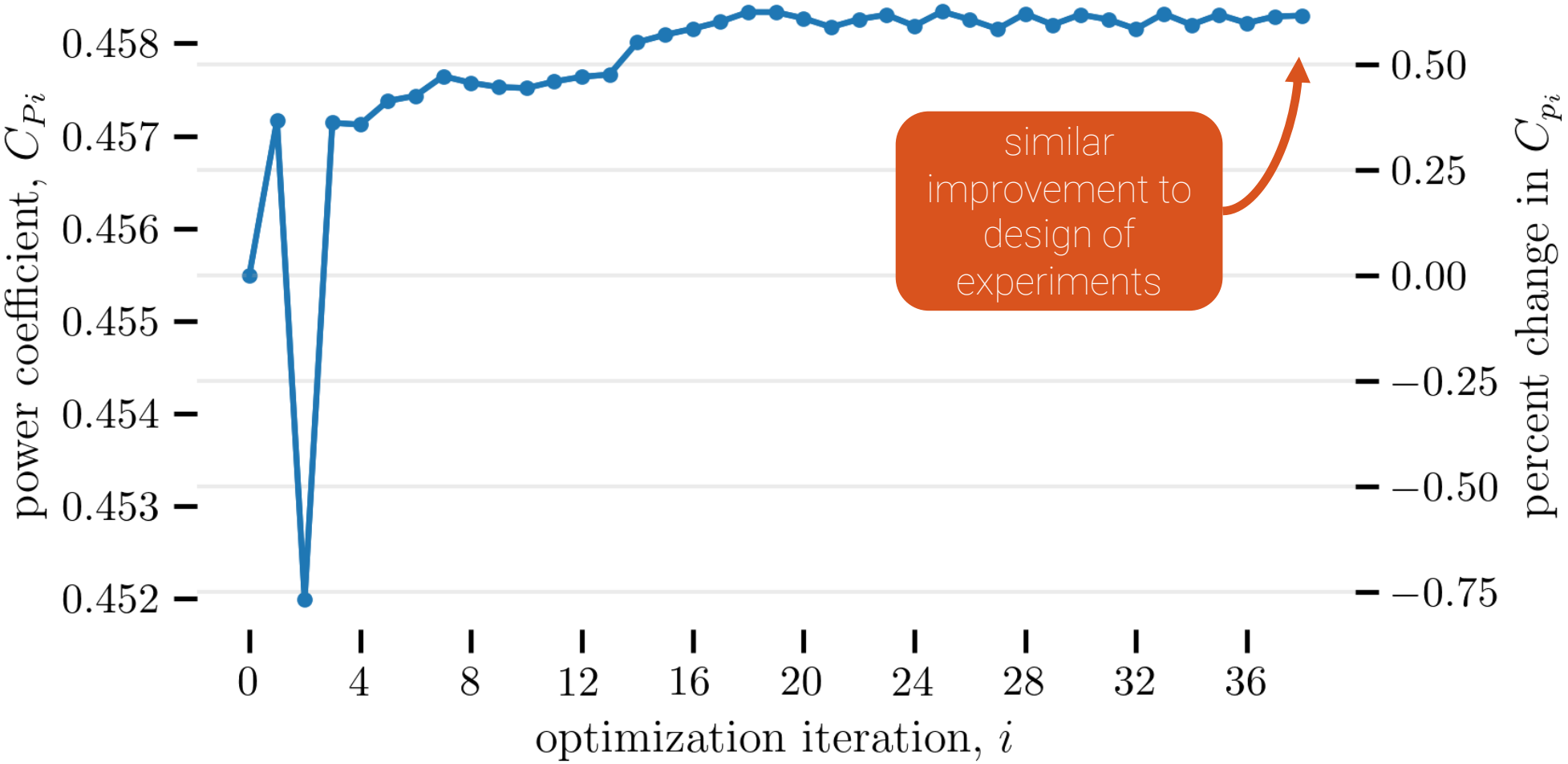
$$\text{subject to F.V.W. E.o.M.}$$

optimization problem implemented with SNOPT (*S*parse *N*onlinear *Opt*imizer)

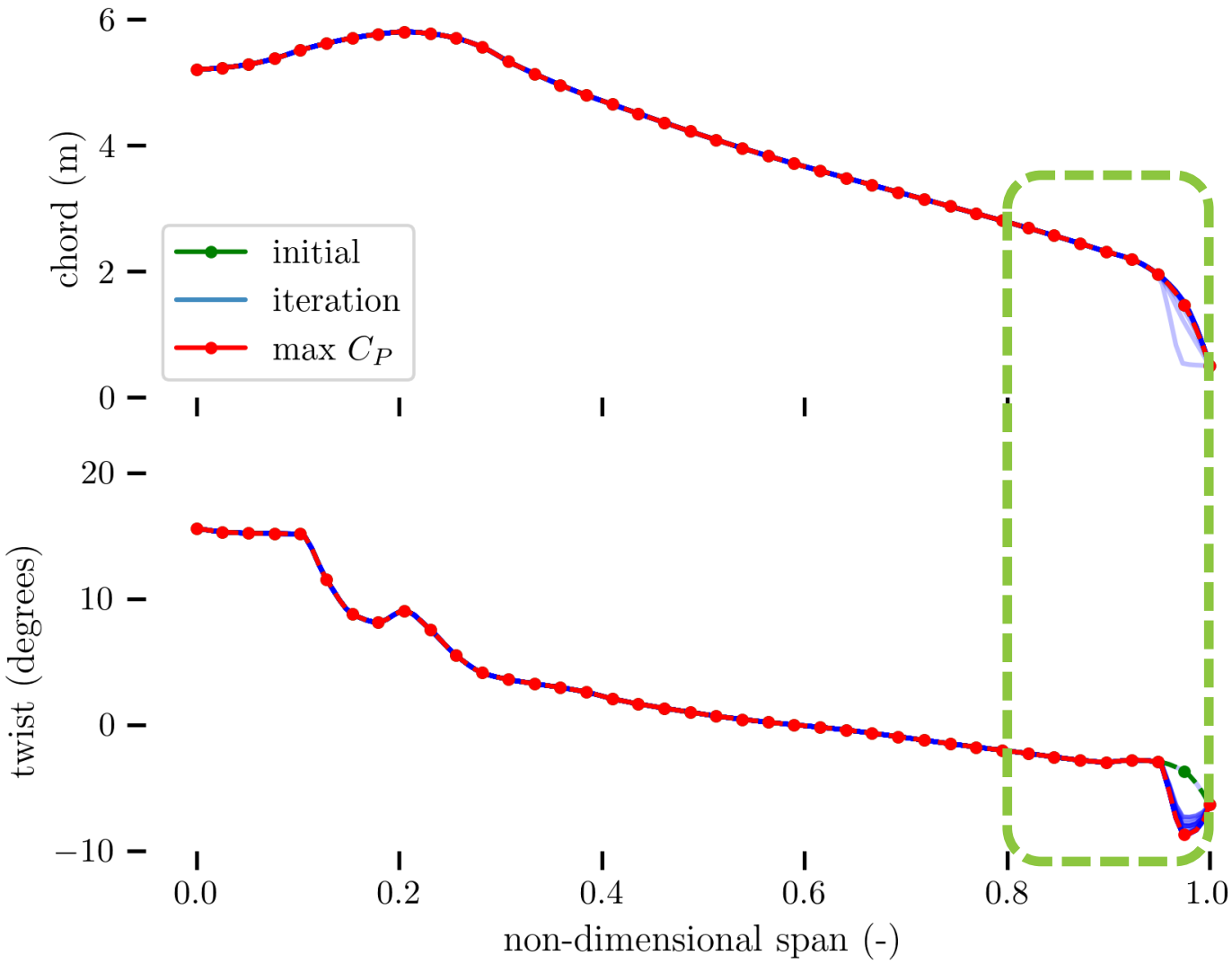
use OLAF FVW, w/ 50 pts.

- not directly comparable to previous solution space
- for cost savings in optimization loop

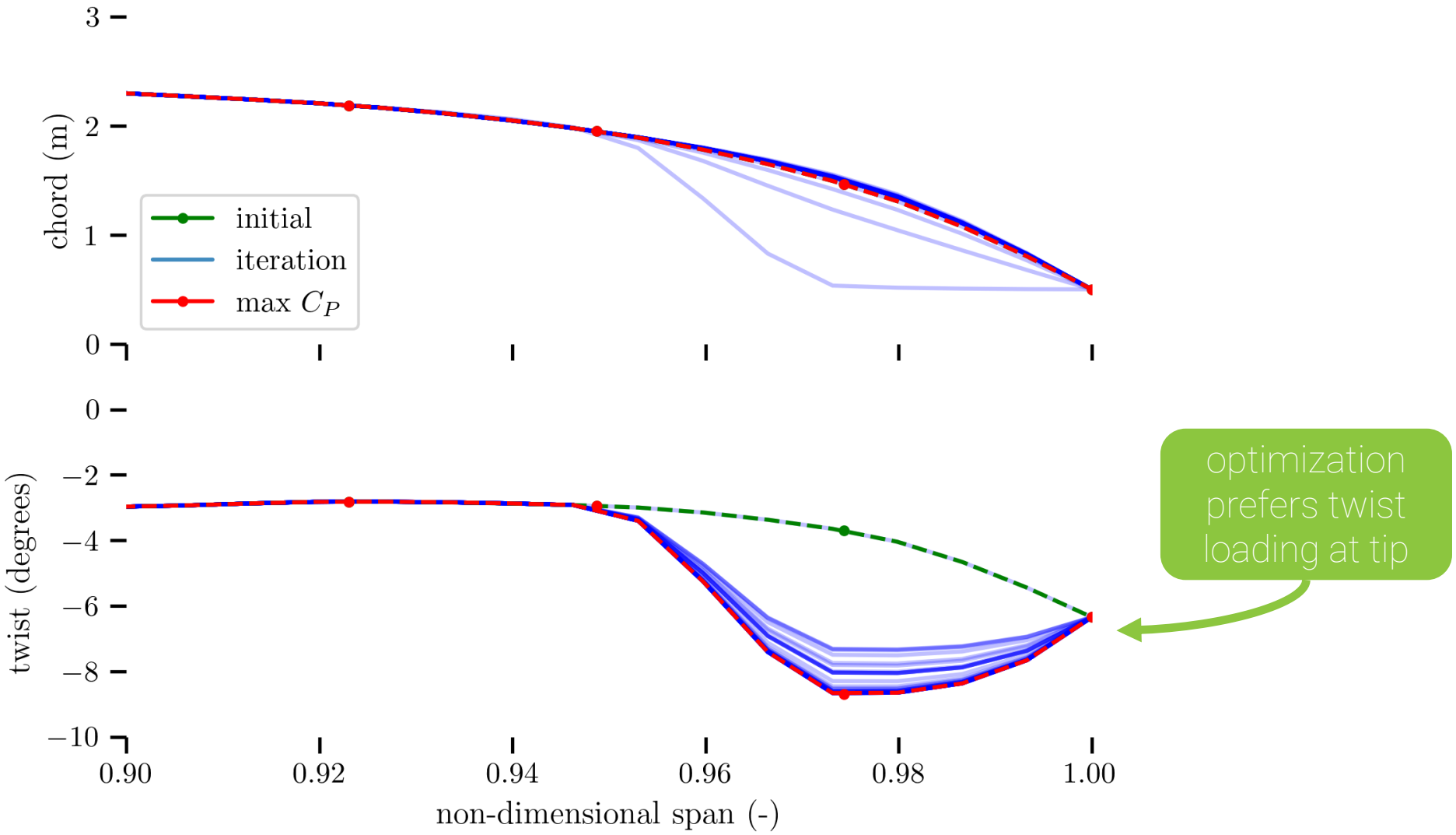
# Optimization: convergence



# Optimization: design iterations



# Optimization: design iterations

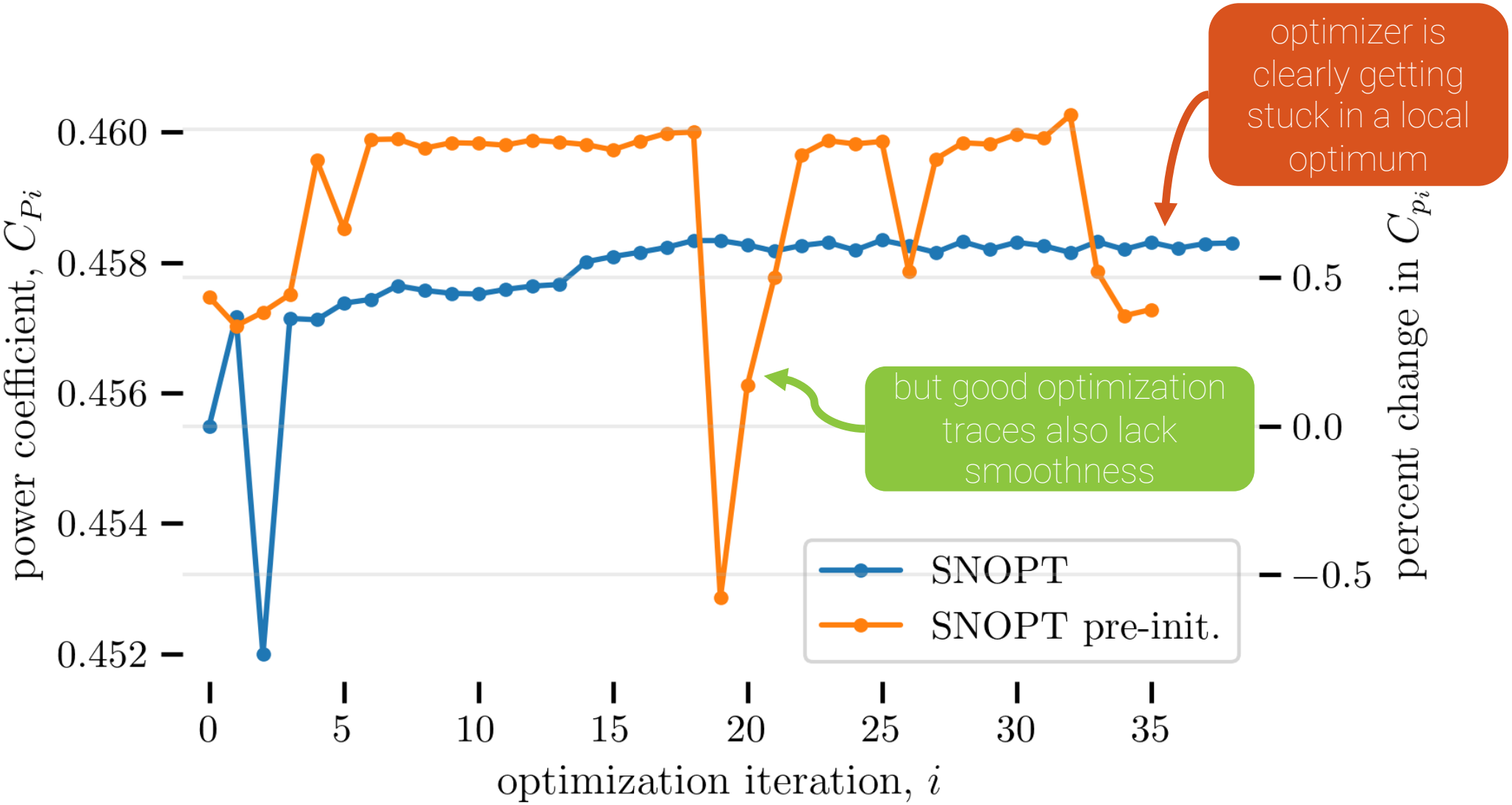


# Optimization/design of experiments disagree

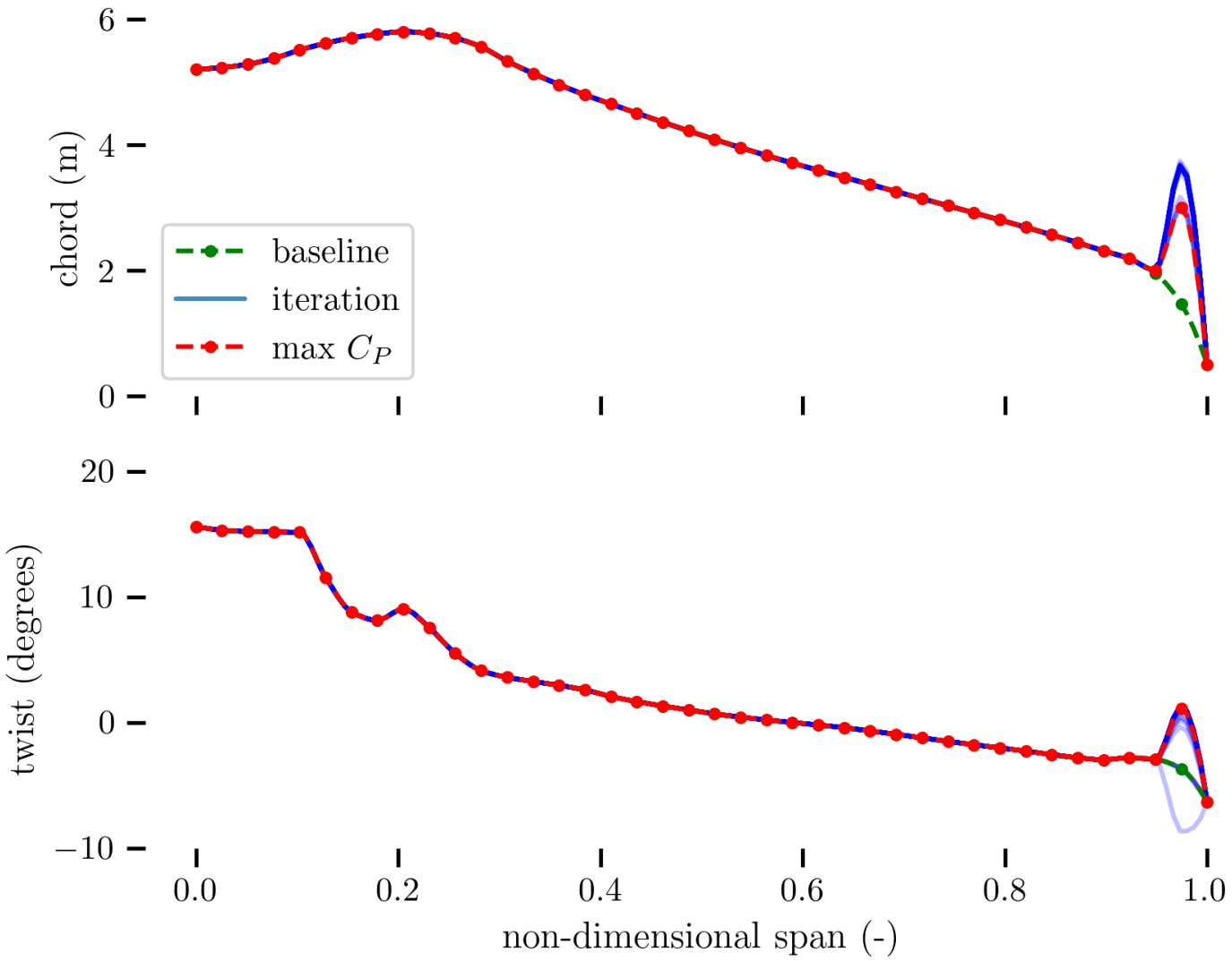
Potential causes:

- (in)stability of FVW solutions
  - FVW: variable-DOF representation of convected vortices
  - highly nonlinear interactions between vortex filaments
  - FVW requires numerical diffusion & truncation
  - are finite-difference gradient computations reliable?
- non-convexity of solution space
  - do local minima prevent global optimality?
- optimization into numerical features
  - is the optimizer attempting to exploit non-physical numerical phenomena?

# Optimization: sensitivity to starting point



# Optimization: coached design iterations



# Conclusions

"Can real wind turbines generate more power than BEM-based designs predict?"

- OLAF FVW solutions discover designs that out-perform traditional BEM-optimal rotors

"Can we create optimal designs using mid-fidelity methods in the design loop?"

- FVW (OLAF) currently inconclusive as a tool for optimization: stability & smoothness concerns
- further research is necessary to enable reliable, robust FVW-in-the-loop design capabilities

# The path forward

Goals:

- improve FVW stability
- improve gradients:
  - differentiable FVW solver?
  - gradient verification
- explore with global optimization toolset
  - verify convergence of local optimization methods
- verify physicality of optimizer-favored phenomena
  - validate optimal designs w.r.t. blade-resolved CFD & experiments
  - will FVW-optimal rotors out-perform BEM-optimal rotors in real use?

# Thank you for your attention!

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy office of Energy Efficiency and Renewable Energy, Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

# References


Madsen M., Zahle F., Horcas S., Barlas T., Sørensen N. “CFD-based curved tip shape design for wind turbine blades.” *Wind Energy Science* 2022; 7(4): 1471–1501. doi:10.5194/wes-7-1471-2022

Barlas T., Pirrung G., Ramos-García N., et al. “Wind tunnel testing of a swept tip shape and comparison with multi-fidelity aerodynamic simulations.” *Wind Energy Science* 2021; 6(5): 1311–1324. doi:10.5194/wes-6-1311-2021

Shaler K., Branlard E., Platt A. OLAF User’s Guide and Theory Manual. Tech. Rep. NREL/TP-5000-75959, 2020

Martínez-Tossas L., Churchfield M., and Meneveau C.. "A highly resolved large-eddy simulation of a wind turbine using an actuator line model with optimal body force projection." *Journal of Physics: Conference Series*. Vol. 753. No. 8. IOP Publishing, 2016.

# Image sources

Betz portrait: Wikipedia, https://en.wikipedia.org/wiki/File:Albert_Betz.jpg

Prandtl portrait: DLR-Archiv Göttingen c/o Wikipedia, https://commons.wikimedia.org/wiki/File:Prandtl_portrait.jpg

OLAF/vortex method screenshots: courtesy of Emmanuel Branlard

Blade-resolved CFD screenshot: courtesy of Ganesh Vijayakumar


NREL
Transforming ENERGY