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

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slides available at:
cfrontin.github.io/NAWEA.pdf

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

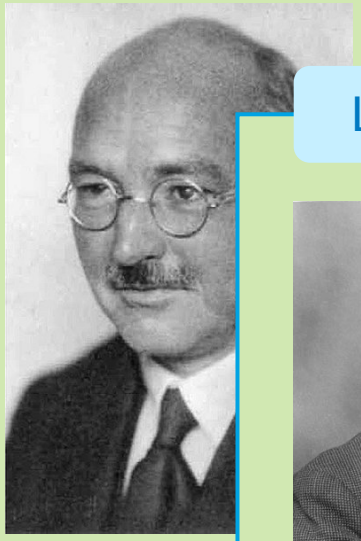
full consideration of coupling
- spanwise vortex distribution
- tip and wake treatment
- radial/spanwise flow/interactions

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

All simulation methods mimic reality

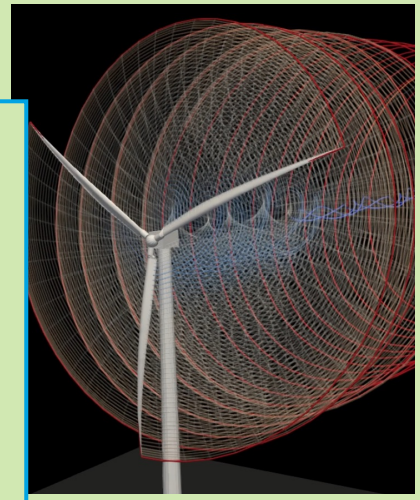
… at different levels of cost and fidelity

BEM

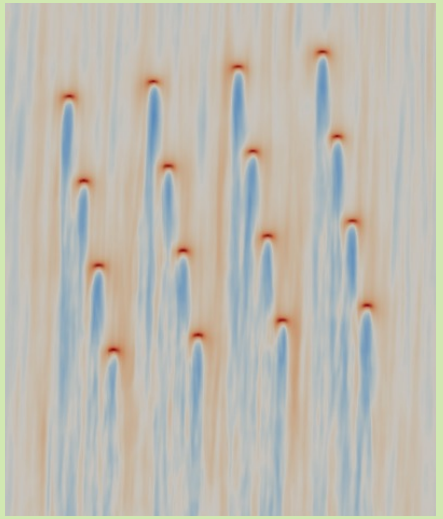


Lifting Lines

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:

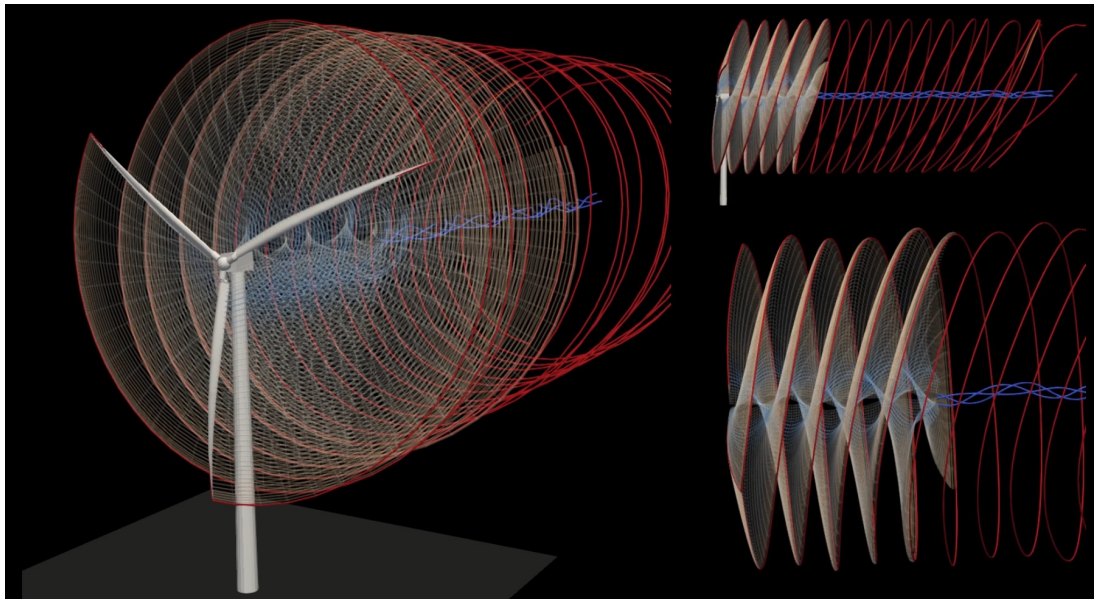
- post-hoc winglet modification for turbine blades
- CFD-based optimization
  - maximize C_P without increasing thrust
  - 1-2% improvement in C_P
  - twist, chord, and tip geometry variation

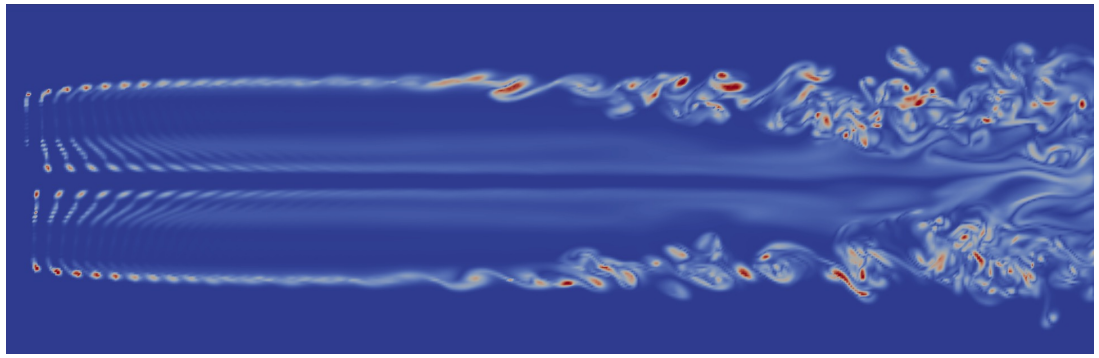
Barlas, et. al., (2021 & 2022):

- 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

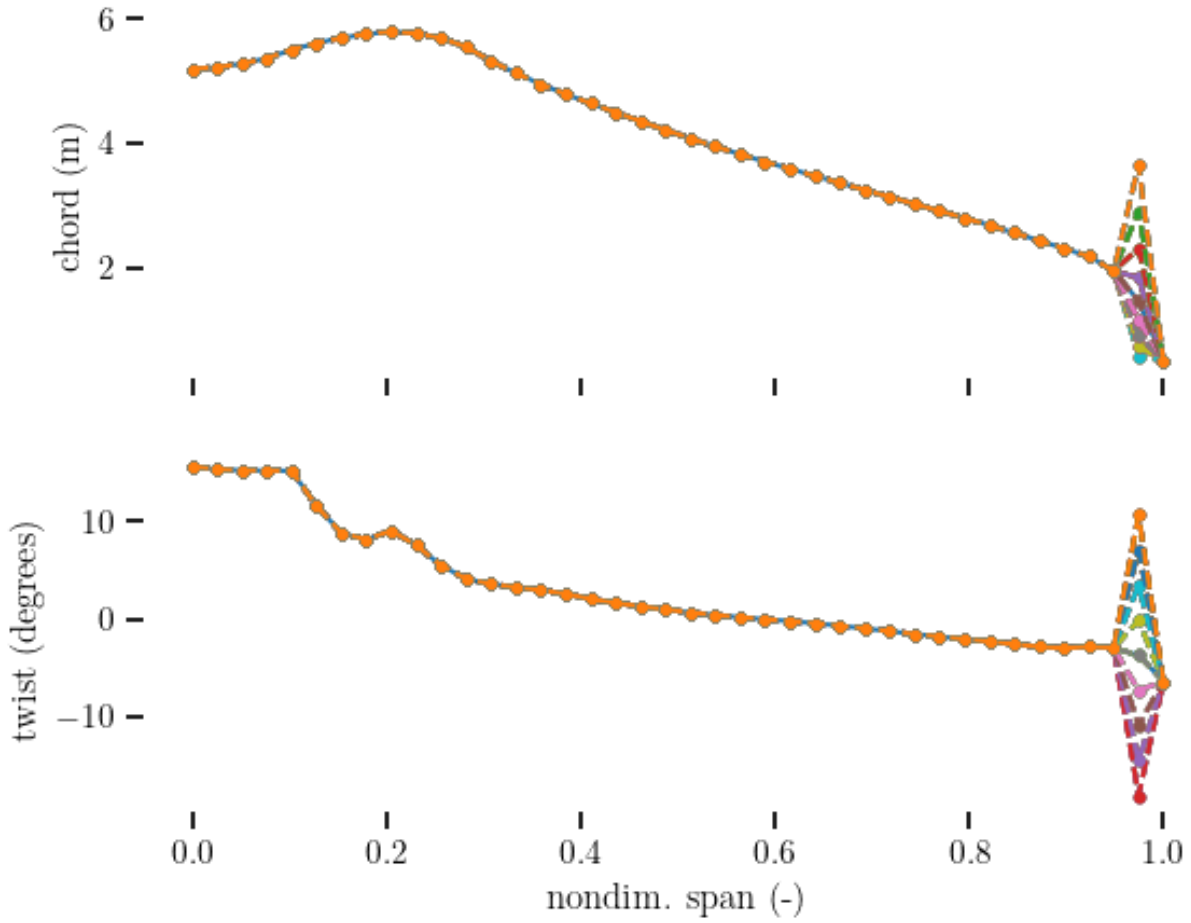




OLAF:

- 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

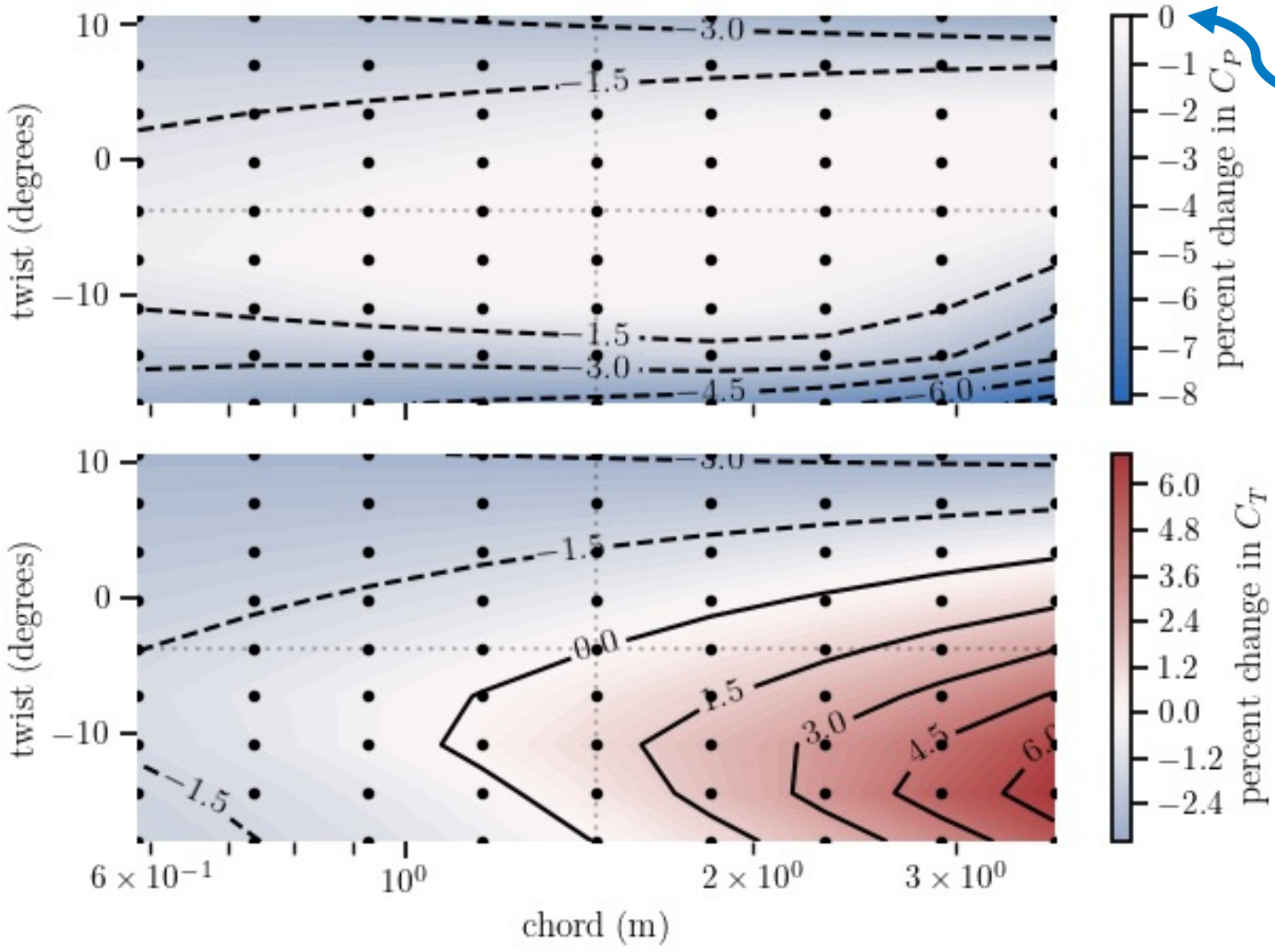
Design of experiments: perturbations



make perturbations

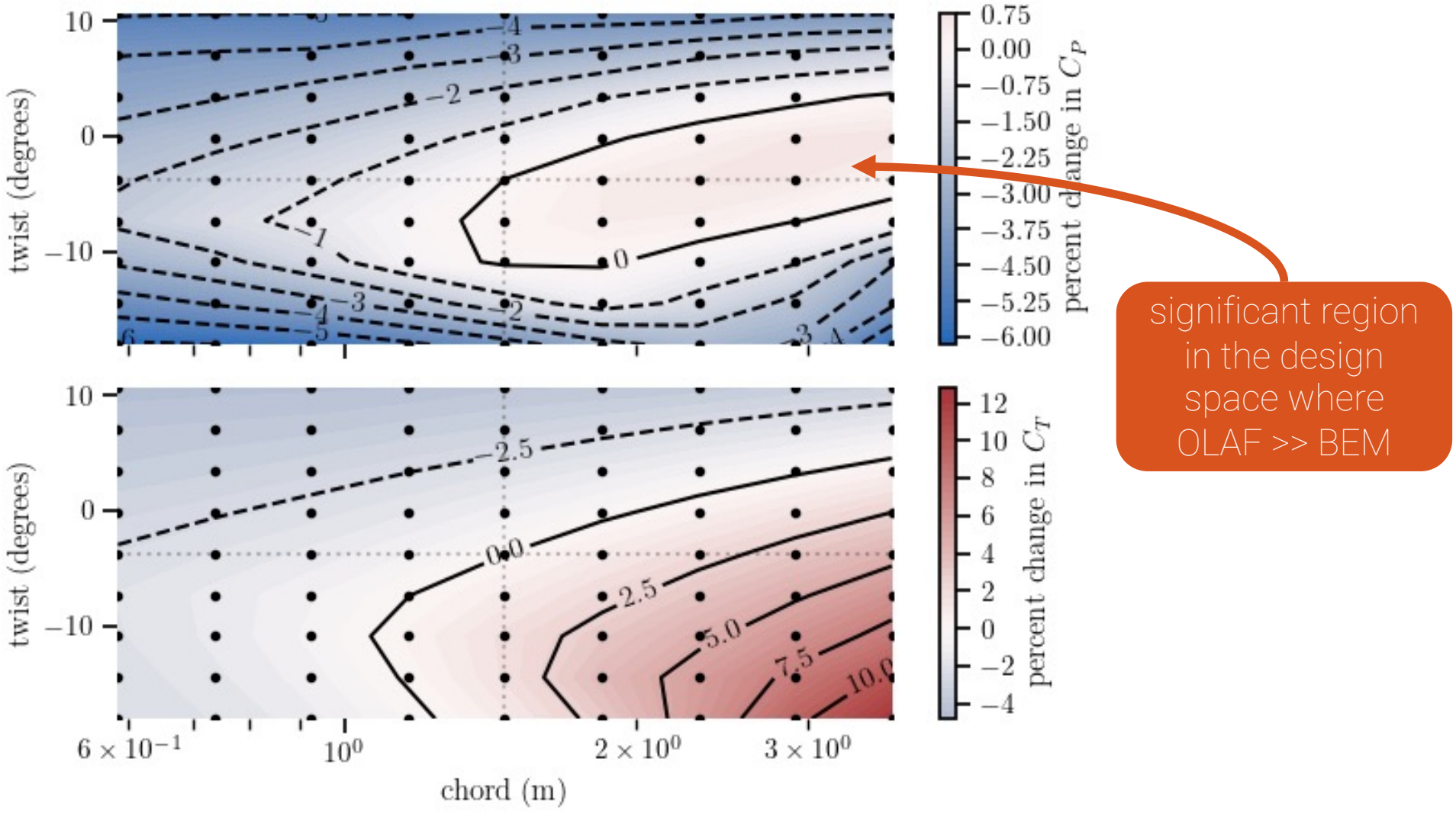
- chord & twist
- 9x9 grid
- at each point: evaluate aero performance
  - BEM
  - OLAF (FVW) w/ 150 pts. (converged)

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

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

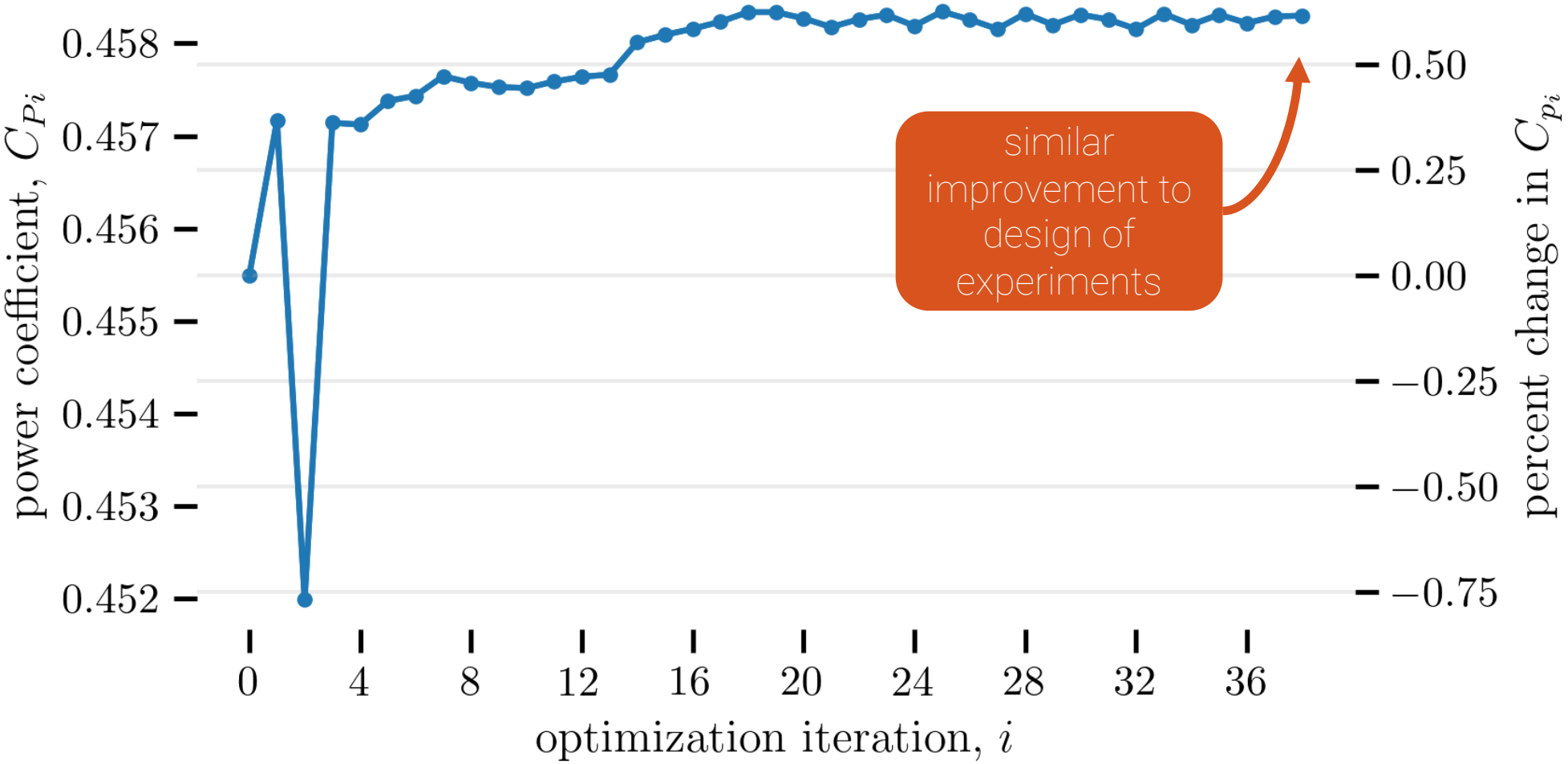
$$\text{subject to F.V.W. E.o.M.}$$

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

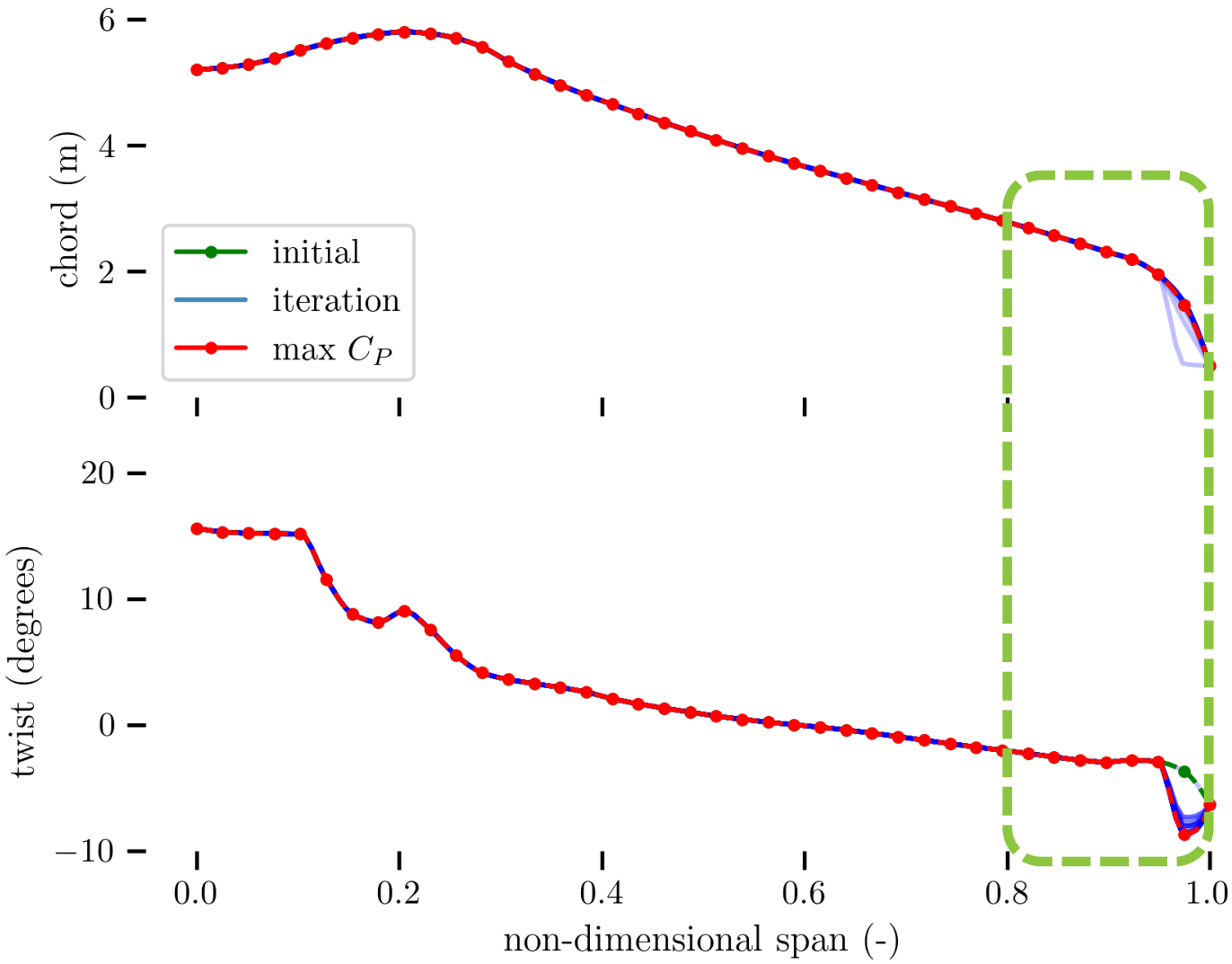
use OLAF FVW, w/ 50 pts.

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

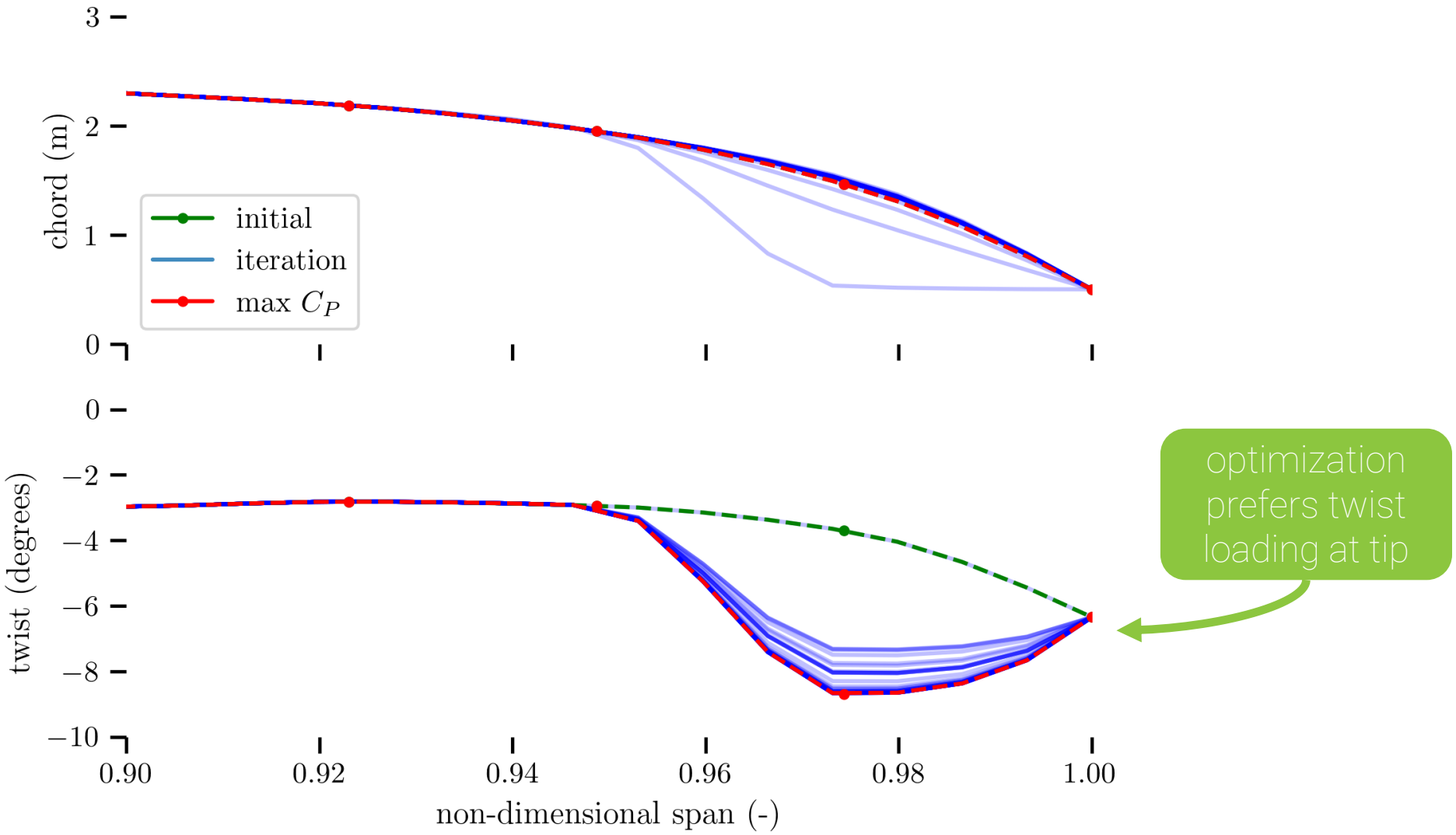
Optimization: convergence



Optimization: design iterations



Optimization: design iterations

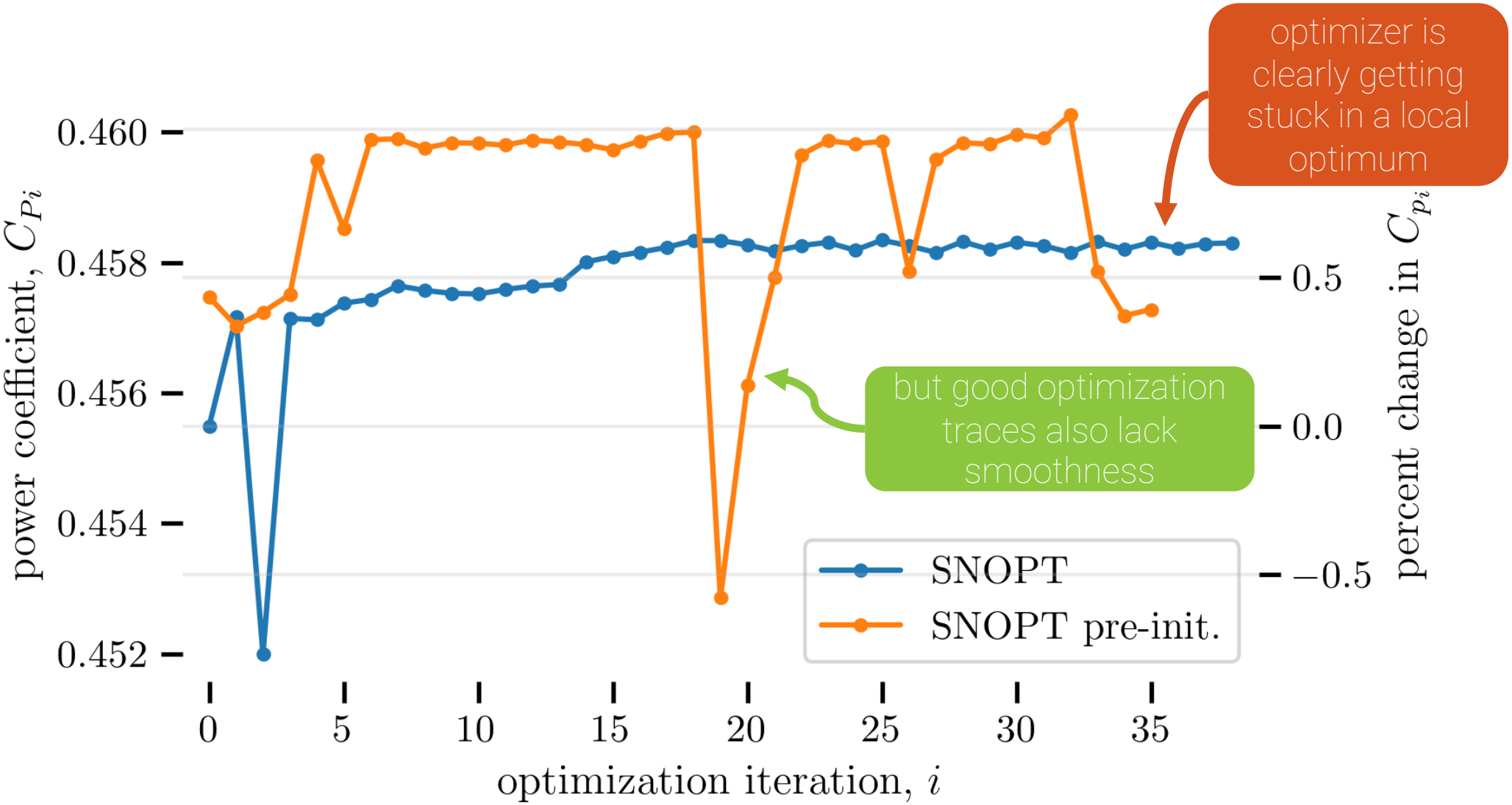


Optimization/design of experiments disagree

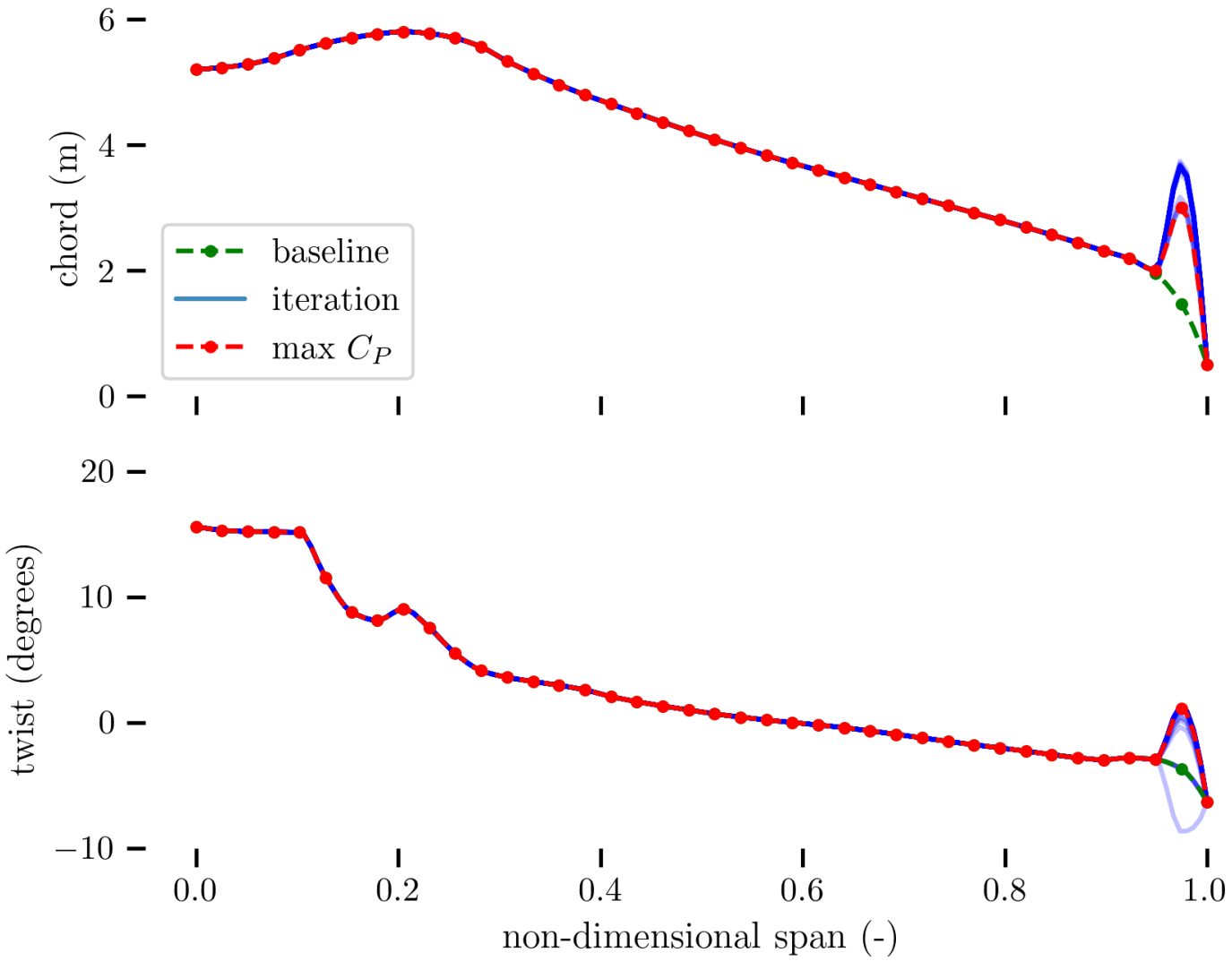
Potential causes:

- (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!

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Image sources

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