Multi-Objective Design of the Rotor System

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Agenda

- Recap: the rotor design problem
- Recap: SWP rotor optimization process
- Application of MDO: Analysis of a design space by comparison of different technology (Pareto) fronts for changing system constraints
- Example: NREL 5MW rotor design problem
- Technical challenges of industrial MDO application
- Conclusions
How to minimize total COE? Accurate cost modelling

- Many disciplines, complex, coupled system, many aspects are unpredictable

  - engineering
  - admin
  - BOM
  - manufacturing
  - transport & construction
  - service
  - balance of station
  - financing

- Cost model that combines various sub-disciplines may not be desirable –
  many ‘costs’ cannot be estimated up-front (i.e. organizational cost, market ‘fit’ etc.)
  or there is insufficient data to construct a meaningful model useful for optimization

- Simplify – solve the problem using a multi-objective approach –
  give decision-makers the data necessary to make trade-off choices directly including
  ‘non-quantifiable’ costs
Recap: Multi-Disciplinary Rotor Design Optimization

Multi-objective rotor design problem w/ non-linear constraints:

- Performance
  - AEP
  - Capacity factor (some markets)
  - Robustness / soiling insensitivity
- Acoustics
  - Site and region specific
- Loads & Controls
  - Normal operation, emergency stop, fault conditions,
  - Blade loads: fatigue and extreme
  - Component loads: fatigue and extreme
- Blade Structure
  - Blade mass / cost
  - Fatigue strain / extreme loads, tip deflection constraint
  - Panel buckling, edge buckling
  - Manufacturing constraints
- Drive Train
  - Generator torque limit
  - Power & frequency converter limits

Simplify to ~3 objective problem, with the rest being constraints- for example, find Pareto front in terms of:

1. AEP
2. Loads Metric
3. Blade Mass

Many ways to setup the problem (nesting etc)

More objectives possible, but for every additional objective, computational cost $x10$
Recap: Technology Front / Multi-Objective Pareto Fronts

A Pareto front gives the set of best possible trade-offs between objectives.
Recap: SWP Rotor Optimization Process

Siemens Blade Optimization Tool (SBOpT) + Galapagos GA Optimizer

- Evaluates 500,000+ blades in an evening within Galapagos and HPC cluster, produces N-dimensional Pareto front between various design objectives

BHawC

- FE code for aero-elastic simulation of entire turbine system
Parameter studies about a fixed planform can only go so far...

Instead, it’s desirable to assess the multi-objective impact of various system constraints / parameters in a way that takes advantage of full design freedom that is available.

Compare Pareto fronts generated for slightly different problems (i.e. constraints, technology assumptions etc.)

- Noise
- Soiling sensitivity
- Allowable tip deflection
- Blade structural technology / material choice
- Component load constraints
- Airfoil selection
- Rated power / rated torque
- Wind resource
- Design for manufacture
- Transportation
- Cost
- and many others...
Advantages of front comparison over conventional parameter/sensitivity studies:

- DOFs are fully exploited (optimized) to take advantage or compensate for system parameter/constraint changes such that solution set is pareto optimal and represents the **fully-coupled impact** of desired change.

- Sensitive to design space location – *design sensitivity in context*

- Optimizer can discover non-intuitive solutions that may be unique to problem description - Useful for challenging conventional wisdom (i.e. *are high modulus materials really necessary?*)
Example Rotor Design: NREL 5MW

- NREL 5MW rotor as described in *NREL/TP-500-38060*

- Spanwise distributions of relative thickness, twist and chord treated as free DOFs
- All other turbine parameters left as-is.
- 1A wind resource
- NREL 5MW evaluated using SWP *Integral Blade*™ structural technology
Example Rotor Design: NREL 5MW
Comparison NREL 5MW Technology Fronts

- 80m/s vs. 90 m/s maximum tip speed planform design Pareto (technology) fronts

90 m/s max tip speed shrinks region 2.5 – better overall aero performance;

Differences only significant for high mass / high load blades

Trade-off for low mass/low load blade is lower outboard solidity, and less able to take advantage of higher tip speed

Slicing plane @ 90% of NREL 5MW load metric
Comparison NREL 5MW Technology Fronts

- Standard vs. 2m additional tip deflection margin planform design technology fronts.

Slice Normalized TechFront at Constant 90 % maxGustLoad

Additional 2m tip deflection allows for ~uniform drop in blade mass/better aero performance resulting from thin cross sections that still have required building height.
Comparison NREL 5MW Technology Fronts

- Both 90 m/s and +2m tipDef planform fronts show vs. standard planform design front

Changes in feasible design space can be compared when co-plotting several technology fronts.

Tech Front Slice at Constant 90% NREL 5MW Max Gust Load

Slicing plane @ 90% of NREL 5MW load metric
Comparison NREL 5MW Technology Fronts

- Both 90 m/s and +2m tipDef planform fronts shown vs. standard planform design front when **sliced at a constant blade mass**

Load reduction possibility vs. NREL 5MW baseline is substantial. **NREL 5MW rotor was intended for reference purposes only**...

Additional 2m tip deflection margin has a greater impact on loads reduction than a higher tip speed
Example Rotor Design: NREL 5MW
Technical Challenges of MDO

- Speed vs. fidelity trade-off OR cycle time vs. confidence level
- Maximizing engineering iterations <1 day cycle time
- Accurate load analogs – full IEC load calculations are time consuming, how can we get 90% of this information for 10% of the computation time?
- Software architecture – working with legacy codes that were not designed with optimization in mind. IT/software challenges often are not fully appreciated. The higher the fidelity of models used, the more this issue is magnified.
Conclusions and Final Thoughts

• The technique of Pareto front comparison has been demonstrated for an example NREL 5MW design space

• Pareto front comparison is useful for evaluating fully coupled impact of technology changes / system parameters on rotor design

• Expert knowledge can be used to inform/tune low and medium fidelity models that make wide ranging design space exploration and exploitation possible in a practical timeframe

• Avoid the rushing immediately to complex models/systems until lower fidelity representations have been exhausted especially when doing optimization

• MDO techniques are not push button – communication and expectations must be managed carefully

• Potential of SE for COE reduction is significant!
MDO Success Stories

- SWT-6.0-154
- SWT-4.0-130
- SWT-3.0-108
- SWT-2.3-108
Thanks for your attention - Questions?

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Example Rotor Design: NREL 5MW

back-up poor-man’s video in case ppt fails…