Multi-fidelity optimization of horizontal axis wind turbines

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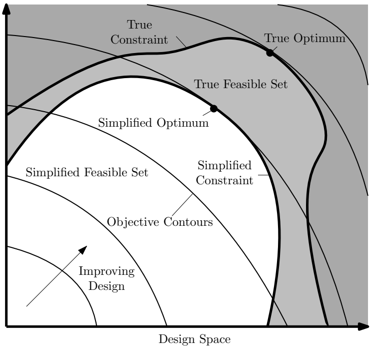
Outline

- The Motivation
- The AMMF Algorithm
- Optimization of an Analytical Problems
- Structural Optimization
    - Low Fidelity Tools
    - Optimization Results
- Aero-elastic Optimization
- Future work
- Closing statements

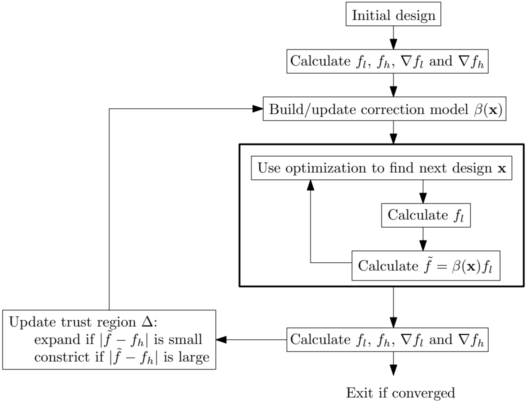
Motivation

- Interested in applying design optimization to advanced concepts:
    - Swept blades
    - Flaps
    - Multi-rotor
- Typical optimization frameworks based on simplified load cases
    - Tuned to be overly conservative
    - Could miss potential opportunities
- Standard design tools and frameworks may not be suitable
    - Need higher fidelity analysis in optimization



The AMMF Algorithm

The AMMF Algorithm



- High fidelity used for accuracy
- Low fidelity is used for speed
- Correction for first order consistency

$$\tilde{f}(\boldsymbol{x}) = f_l(\boldsymbol{x}) + \beta(\boldsymbol{x})$$

$$\beta(\boldsymbol{x}) = f_{h0} - f_{l0} + (\nabla f_{h0} - \nabla f_{l0})\, \Delta \boldsymbol{x}$$

- Trust-region for robustness

Constraints in the AMMF Algorithm

- Constraints are corrected in the same way
- The constraints are present in the low fidelity optimization
- Constraints receive special treatment in Approximation and Model Management Framework (AMMF)
- First an estimated Lagrangian is calculated

$$\Phi = f + \tilde{\lambda}_e \cdot |\boldsymbol{c}| + \tilde{\lambda}_i \cdot \max(0, -\boldsymbol{c}_i)$$

  - $\tilde{\lambda}$ are the Lagrange multipliers estimated from previous iterates.
  - $\tilde{\lambda}$ is specified for the first iteration
- New iterate only accepted when $\Phi_i < \Phi_{i-1}$
- Trust region is expanded or contracted based on M:

$$M = \frac{\Phi_{i-1} - \Phi_i}{\Phi_{i-1} - \tilde{\Phi}_i}$$

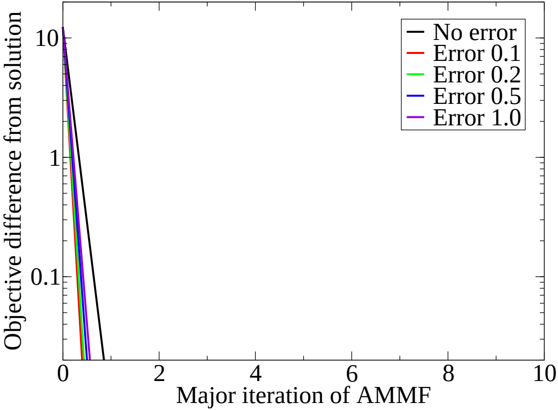
  - Trust region expanded if M is close to 1
  - Trust region contracts if M is far from 1

Preliminary investigation into AMMF

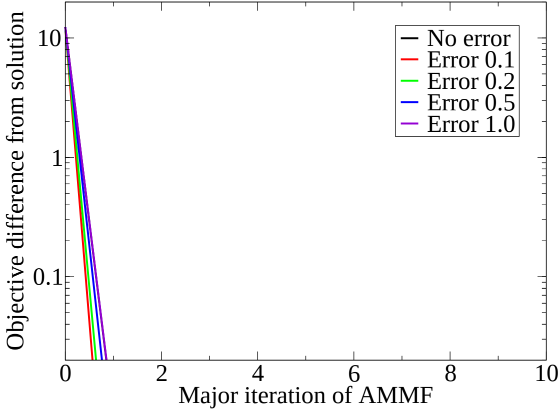
Preliminary investigation into AMMF

- Objective
  - Understand how different types of error affect AMMF convergence
- Methodology
  - Used a simple 2D paraboloid optimization problem
  - Applied various offsets to simulate error in the low-fidelity model
  - Number of function evaluations used to assess computational cost
- Phase 1: Order of the error
  - Constant offset, linear offset & quadratic offset

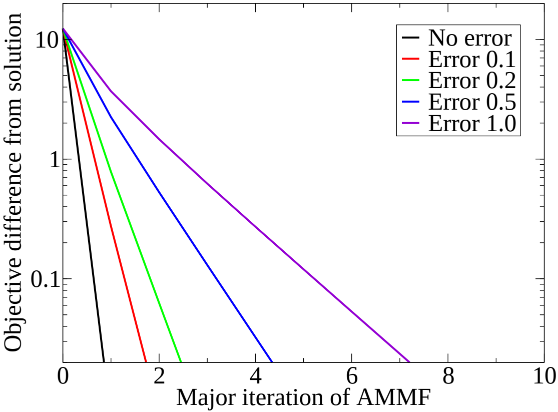
Effect of constant offset error on AMMF



Effect of linear offset error on AMMF

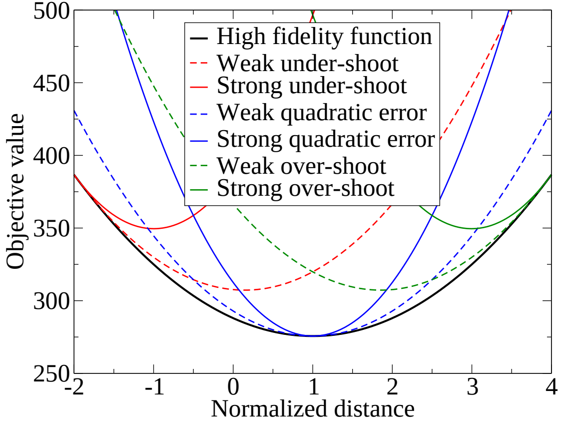


Effect of quadratic offset error on AMMF

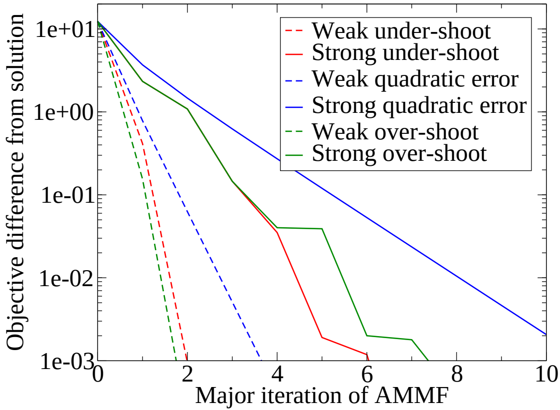


AMMF investigation phase 2: Lateral offset errors

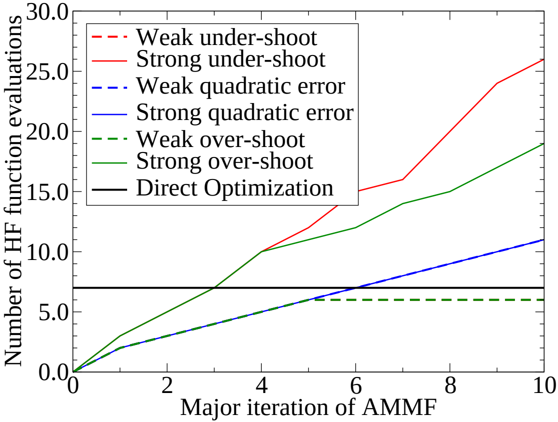
- Under or over-shooting low fidelity model



AMMF convergence rate vs. lateral offset error



AMMF function evaluations vs. lateral offset error



Preliminary investigation summary

- Only affected by quadratic and higher order error
- Trust region is used to correct lateral offset error
- Extreme error requires more high fidelity function evaluations
- Best-case:
  Only 2-3 high fidelity function evaluations are required for convergence
- Worst-case:
  Convergence is the same as pure high fidelity optimization

Multi-fidelity Structural Design Optimization

Low Fidelity Tool Development

Summary of Low Fidelity Tools

Position	EA	EIx	EIy	GJ
0.05	0.0	2.6	-4.9	-5.4
0.15	0.5	1.1	-3.0	-0.8
0.25	-0.4	-1.8	2.1	-1.4
0.35	-0.7	-2.6	1.7	-3.1
0.45	-0.7	-3.1	1.0	-5.5
0.55	-0.9	-3.1	-0.3	-7.7
0.65	-0.8	-2.9	-1.7	-9.3
0.75	-0.6	-2.2	-2.2	-9.2
0.85	-0.6	-1.7	-3.5	-5.9
0.95	-0.1	-1.2	-2.0	-2.0

Table : Percent Error with BECAS

- Low fidelity cross section tool
    - Thin-walled cross section assumption
    - Rigid cross section (Euler-Bernoulli)
    - Classic laminate theory
    - Written in C++
    - Python bindings with Swig
    - Will have analytic gradients
    - Within 10% compared to BECAS

Summary of Low Fidelity Tools

Operation	Calculation time [s]
Linear Beam Model	0.0035
LF cross section model	0.0074
BECAS	200.1866

Table : Speed Comparison of Low Fidelity Tools

- Linear Beam Model
  - C++ code from my PhD
  - Analytic gradients wrt.
    - Positions
    - Orientation
    - Cross section properties
    - Applied forces
  - Solves equivalent forces for given deflection
- Speed comparison:
  - With python bindings
  - Calculation for whole blade
  - 19 elements
  - DTU $10MW$

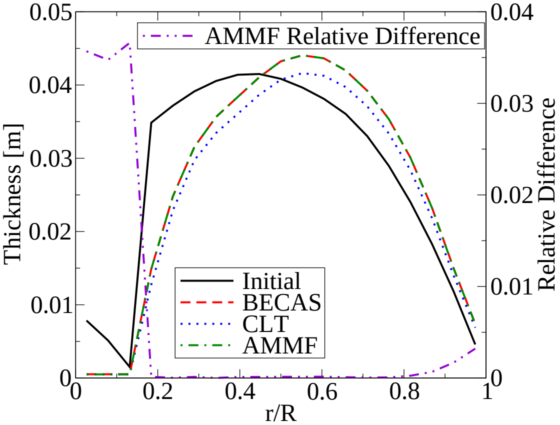
AMMF for equivalent static beam

Problem Description

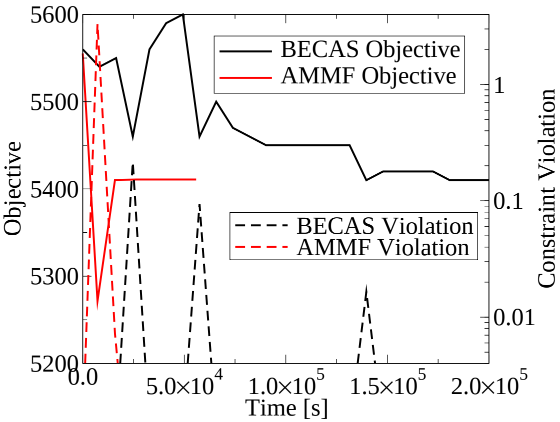
- Minimize DTU 10MW Blade Mass
- Varying spar cap thickness
- Subject to:
  - Tip deflection constraint
- Analysis based on the equivalent static problem (*i.e.* Frozen loads)
- Compared pure BECAS, pure CLT and AMMF
- Looked at various AMMF configurations:
  - Additive vs. Multiplicative corrections
  - Trust region size
  - Initial Lagrange multiplier (*i.e.* Penalty parameter)

Optimization Results

- Low fidelity model is not conservative
    - Will produce infeasible solutions
- AMMF reproduced the BECAS solution
    - AMMF had better constraint resolution
- AMMF gives accurate corrections
- Additive vs multiplicative corrections:
    - Gives similar solutions
    - Similar performance



Optimization Convergence

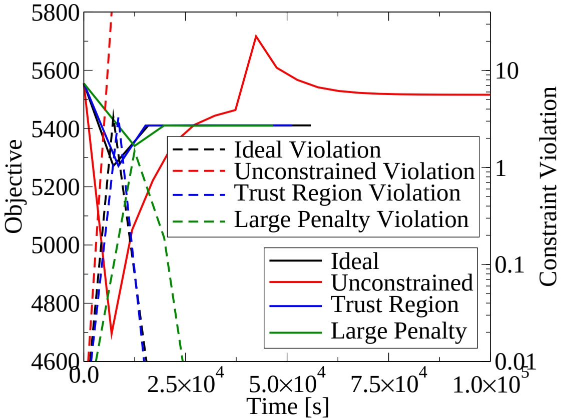


- AMMF converges 12 times faster
    - Just 2 major iterations
- AMMF had smoother convergence
    - Only 1 iteration with constraint violation
    - BECAS optimization ended due to maximum iterations
- Low fidelity models more suitable for optimization

AMMF Robustness

AMMF guards against poor approximations

- Unconstrained has all protections disabled
  - Large violations
  - Fails to converge
- Trust region is most robust
  - Same progress as ideal configuration
- Large penalties work without trust region
  - No large violations
  - More searching

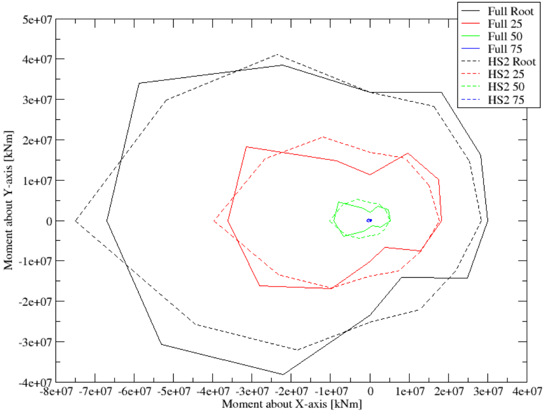


AMMF for aero-elastic blade design

Problem Description

- Maximize DTU 10MW AEP
- Varying all blade design parameters
- Subject to:
  - Tip deflection constraint
  - Stress constraints
  - Geometric constraints
- Analysis based on BECAS, HAWCStab2, HAWC2
- Used a reduced DLB
  - Preliminary optimization to see if it runs
  - Future work will use a full DLB
- Low-fidelity model based on corrected HAWCStab2 results

Low-Fidelity Work-flow



$$M_{dyn} = M_{static} A(r) \sigma \frac{dM}{dV}$$

- Model for the dynamic loads M_{dyn} based on:
  - HAWCStab2 moment loads M_{static} and $\frac{dM}{dV}$
  - Turbulence σ
  - Correction $A(r)$
- Matches full DLB
  - Used Dakota to tune A based on $\min R^2$
- No HAWC2 but still needs 75% of the time

AMMF Optimization Results

- AMMF ran in MPI
- Only 1 iteration achieved within cluster time limit
    - Similar run time between low & high fidelity
- AMMF moving in the right direction
- Increase in AEP
    - Direct 6.17%
    - AMMF 4.61%
    - 74.7% progress
- Blade failure index $0.79 < 0.9$
    - AMMF was conservative

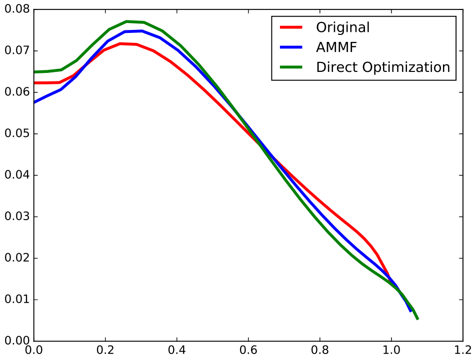


Figure : Normalized Chord vs. Blade Radius

Future Work

Ongoing Aero Elastic Design Optimization

Table 1: Overview of the Design Load Basis of DTU Wind Energy. For turbines with storm operation the wind speed range must be adjusted accordingly.

Name	Load	PSF[1]	Description	WSP [m/s]	Yaw [deg]	Turb.	Seeds	Shear	Gust	Fault	T [s]	Files
DLC11	U	1.25	Normal production	4:2:26	-10/0/+10	NTM	6	0.2	None	None	600	216
DLC12	F	1.0	Normal production	4:2:26	-10/0/+10	NTM	6	0.2	None	None	600	216
DLC13	U	1.35	Normal production	4:2:26	-10/0/+10	ETM	6	0.2	None	None	600	216
DLC14	U	1.35	Normal production	Vr+/-2,Vr	0	None	None	0.2	ECD	None	100	3
DLC15	U	1.35	Normal production	4:2:26	0	None	None	Eq. in IEC	EWS	None	100	48
DLC21	U	1.35	Grid loss	4:2:26	-10/0/+10	NTM	4	0.2	None	Grid loss at 10s	100	144
DLC22p	U	1.1	Pitch runaway	12:2:26	0	NTM	12	0.2	None	Max. pitch to fine at 10s	100	96
DLC22y	U	1.1	Extreme yaw error	4:2:26	15:15:345	NTM	1	0.2	None	Abnormal yaw error	600	276
DLC22b	U	1.1	One blade stuck at min. angle	4:2:26	0	NTM	12	0.2	None	1 blade at fine pitch	600	144
DLC23	U	1.1	Grid loss	Vr+/-2, Vout	0	None	None	0.2	EOG	Grid loss at three diff. times	100	9
DLC24	F/U	1.0	Production in large yaw error	4:2:26	-20/+20	NTM	3	0.2	None	Large yaw error	600	72
DLC31	F	1.0	Start-up	Vin, Vr, Vout	0	None	None	0.2	None	None	100	3
DLC32	U	1.35	Start-up at four diff. times	Vin, Vr+/-2, Vout	0	None	None	0.2	EOG	None	100	16
DLC33	U	1.35	Start-up in EDC	Vin, Vr+/-2, Vout	0	None	None	0.2	EDC	None	100	16
DLC41	F	1.0	Shut-down	Vin, Vr, Vout	0	None	None	0.2	None	None	100	3
DLC42	U	1.35	Shut-down at six diff. times	Vr+/-2, Vout	0	None	None	0.2	EOG	None	100	18
DLC51	U	1.35	Emergency shut-down	Vr+/-2, Vout	0	NTM	12	0.2	None	None	100	36
DLC61	U	1.35	Parked in extreme wind	V50	-8/+8	11%	6	0.11	None	None	600	12
DLC62	U	1.1	Parked grid loss	V50	0:15:345	11%	1	0.11	None	None	600	24
DLC63	U	1.35	Parked with large yaw error	V1	-20/+20	11%	6	0.11	None	None	600	12
DLC64	F	1.0	Parked	4:2:0.7 Vref	-8/+8	NTM	6	0.2	None	None	600	192
DLC71	U	1.1	Rotor locked and extreme yaw	V1	0:15:345	11%	1	0.11	None	Rotor locked at 0:30:90 deg	600	96
DLC81	U	1.5	Maintenance	Vmaint	-8/+8	NTM	6	0.2	None	Maintenance	600	12
										Totals	259h	1880

Figure : The full IEC 61400 Design Load Cases

- High fidelity based on HAWC2, the full set of International Electrotechnical Commission (IEC) 61400 design load cases with turbulence
- Low fidelity based on Classical Laminate Theory (CLT) and a reduced set of load cases without turbulence

Swept Blade Design Optimization

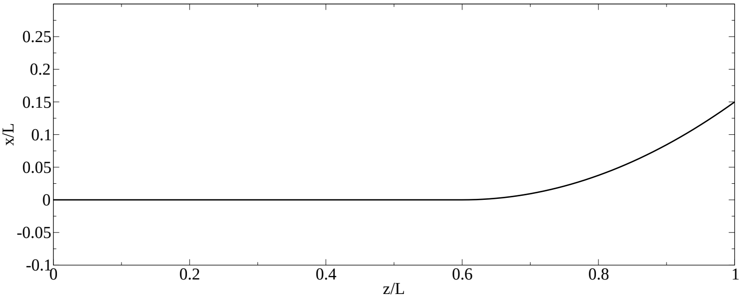


Figure : Swept Blade Shape

- High fidelity based on HAWC2 and Omnivor (time marching vortex code)
- Low fidelity based on HAWCStab2
- Aerodynamic only design optimization

Closing Statements

Conclusions

- Promising results for Multi-fidelity optimization
  - With the right low-fidelity model AMMF is 12 times faster
  - AMMF is robust against model and correction errors
- AMMF can perform aero-elastic blade optimization
  - AMMF work-flow needs more refinement for aero-elastic optimization
  - Trying to include the full IEC 61400 DLC for high fidelity analysis
- Working on applying AMMF on a swept blade aerodynamic optimization

Acknowledgments

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Thank-you for your interest

Comments or Questions?