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Paving The Way For Wind Farm Control In Industry

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Turbine loading in wind farm control: requirements and modelling approach

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Controlling wakes in wind farms

DNV·GL

- Reduced power!
- increased loading!

Switch this turbine off?

Traditional sector management

Or reduce the power set-point of this one?

"Induction control"

Or maybe yaw the turbine slightly to steer its wake away from the next turbine?

"Wake steering"

1. What is the **optimum*** distribution of power and yaw setpoints for all the turbines, in this wind condition?
2. How can we maintain **optimum*** performance in dynamically changing circumstances?

* Optimum has to be defined – depends on energy and loading

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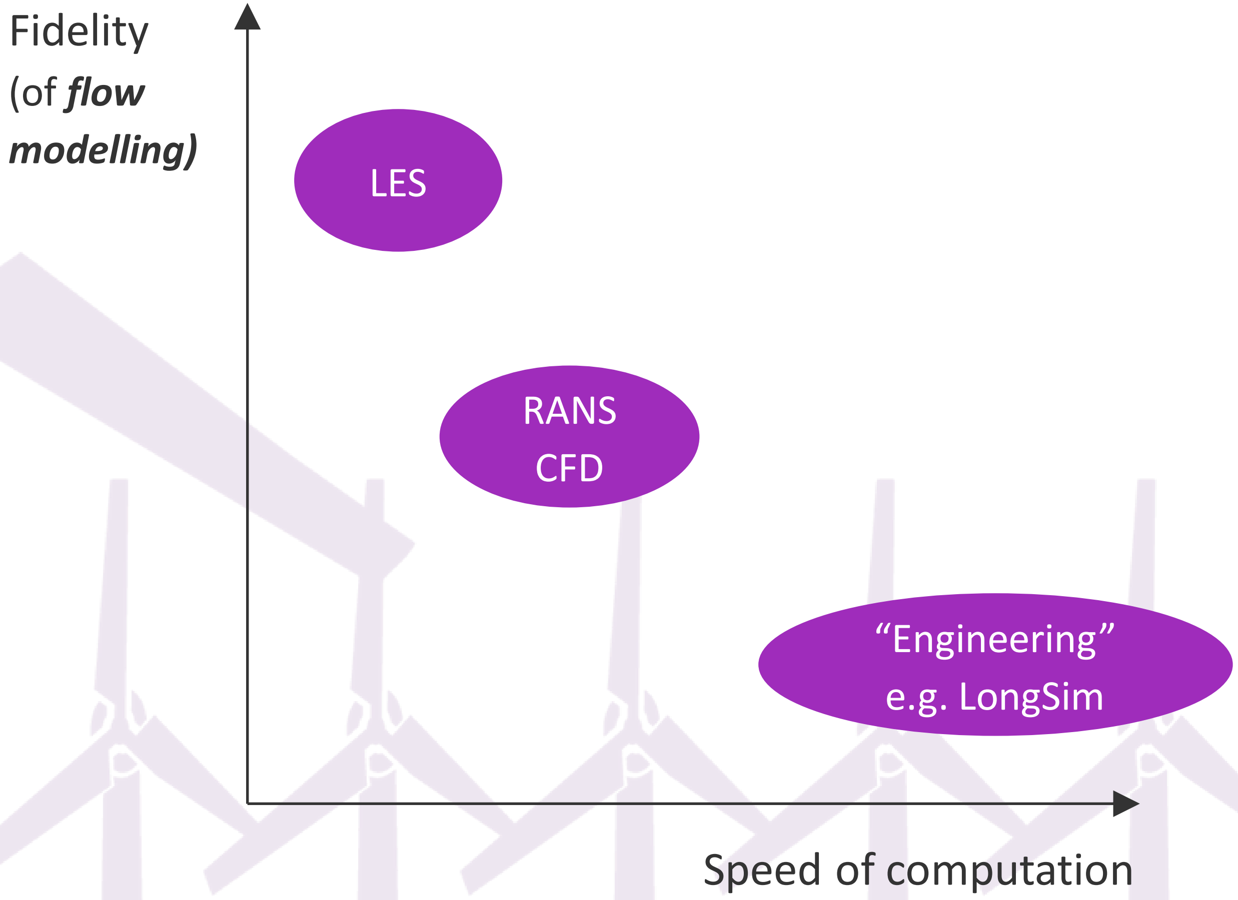
Modelling requirements

- Detailed representation of turbine wakes in different atmospheric conditions
- Realistic, time-varying wind conditions
- Accurate modelling of turbine control dynamics
- Needs time-domain simulations
  - Long enough to capture low-frequency wind variations (hours, days, weeks)
  - Short enough timestep (~1s) to capture principal turbine and wind farm control dynamics
  - Fast enough to run many repeat simulations for design iterations

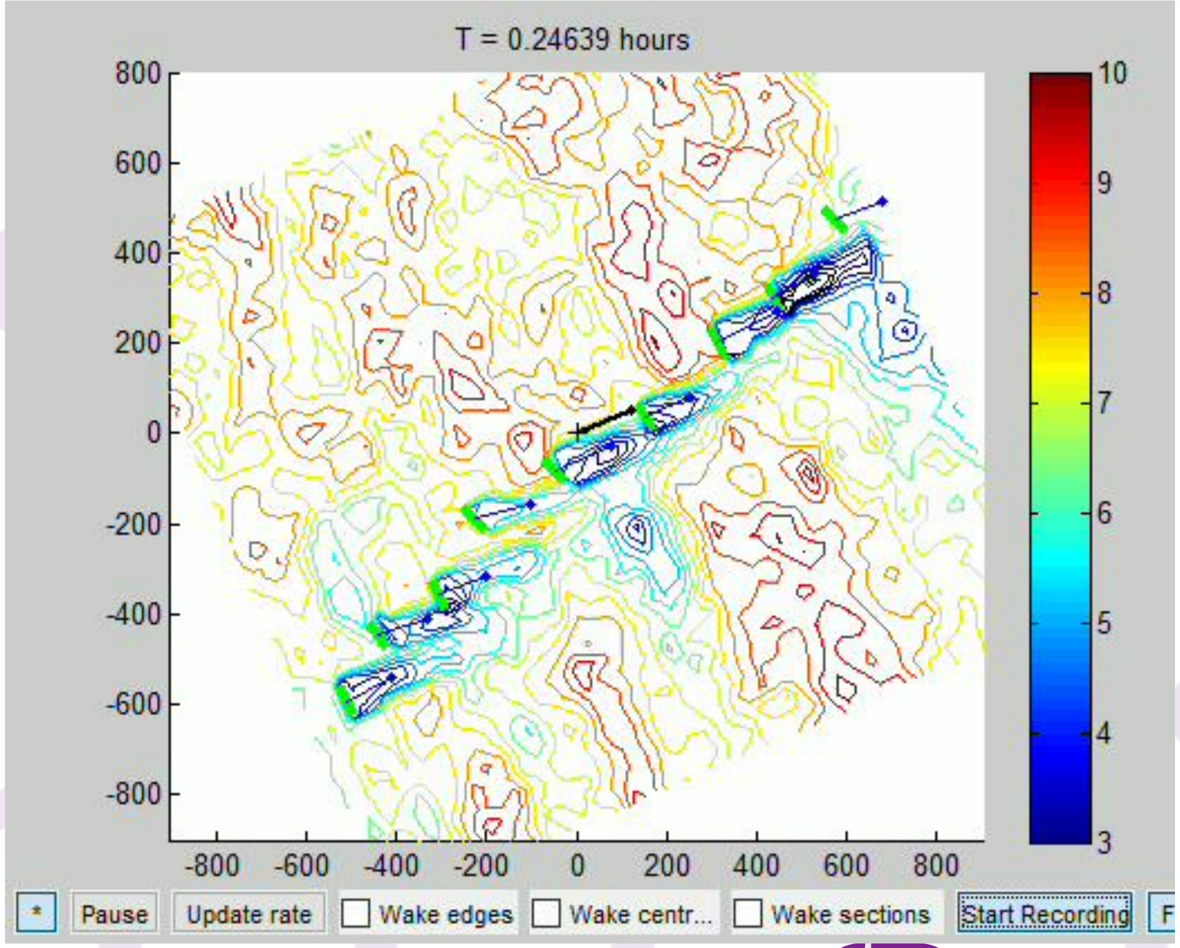


Time-domain simulation - LongSim

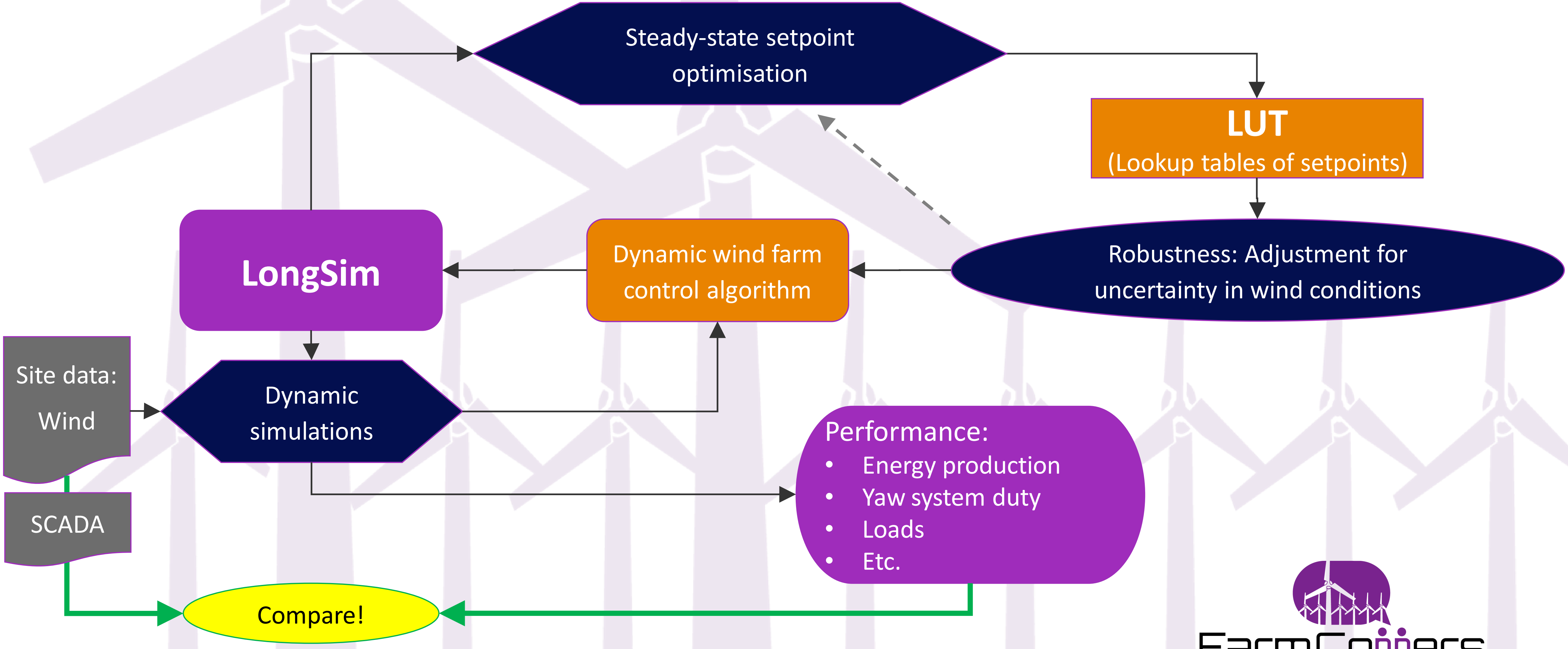
- Choice of engineering wake models, embedded in stochastic flow field
  - Profile: e.g. Ainslie or Bastankah, other variations
  - Options for Wake turbulence, superposition, lateral deflection etc.
- Wake meandering and advection
- Turbine details, including supervisory control
- Wind farm control algorithm
  - Estimation of wind conditions from turbine signals
  - Setpoint lookup
  - Setpoint implementation

Example with wake steering: Sedini wind farm, Italy

- Wind field generated from historical site data (met mast)
- Test & tune control algorithm details
- Test controller against different wake models
- Evaluate power increase, yaw actuator duty etc.



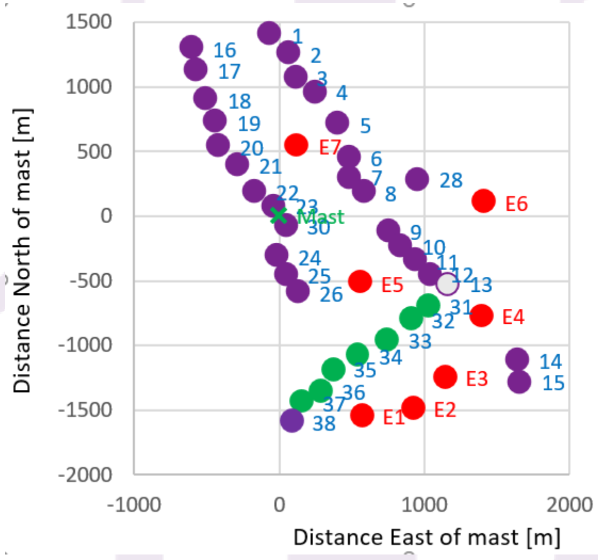
Wind farm control – design process

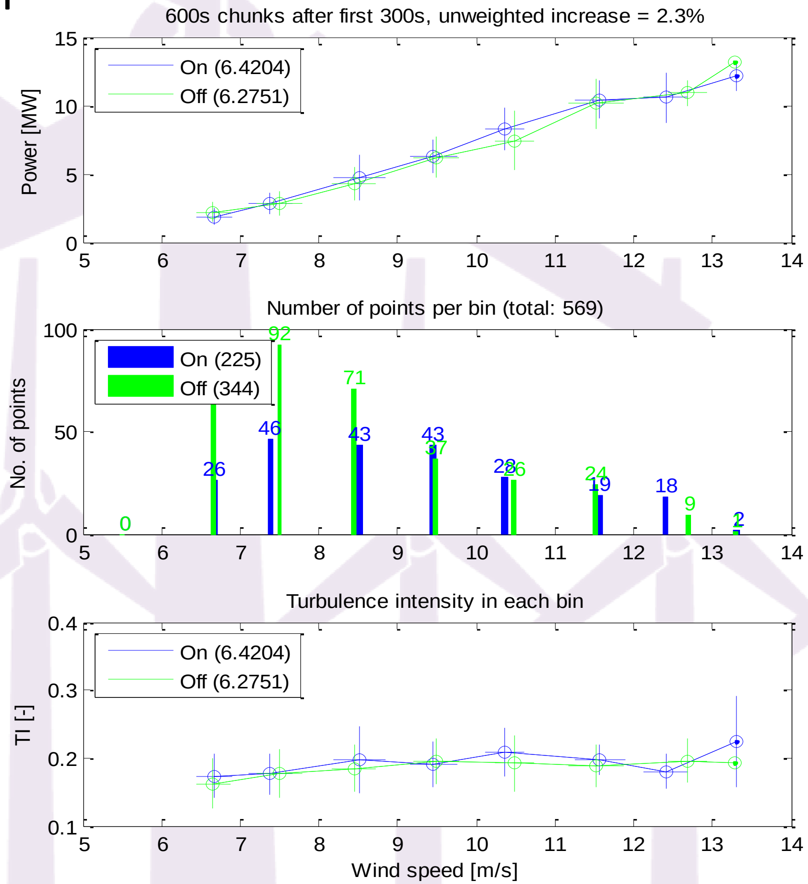


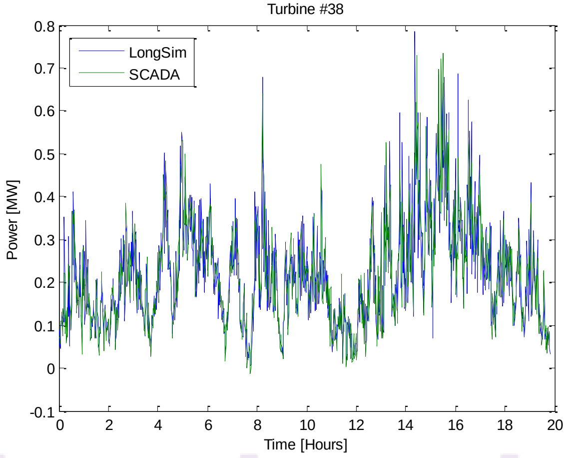
Wind farm control – real example (Sedini)

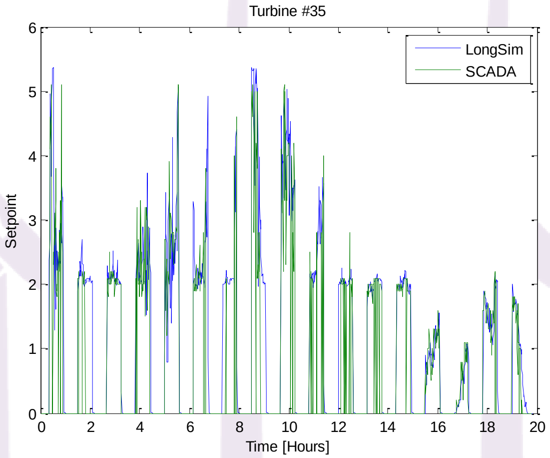
Axial induction control – row of 9 turbines

- Steady-state setpoint optimisation
- Smoothing for robustness
- Simulation test (Longsim)
- Toggle test in the field
- Companion simulations









What about loads?

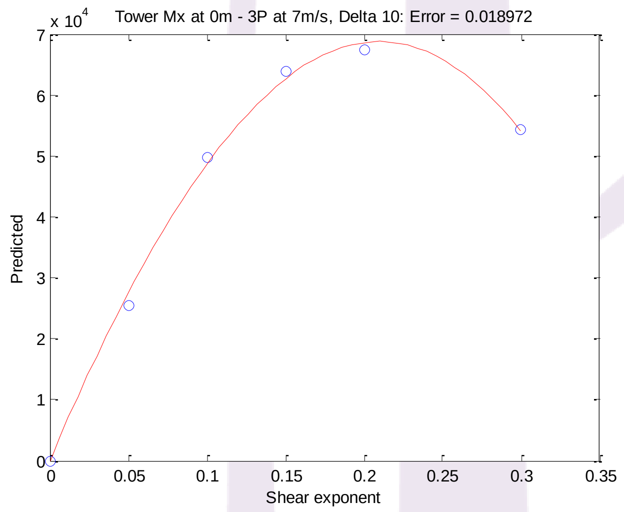
- Turbine loads are affected by wakes. Site-specific loading calculations would ideally look at every turbine in the wind farm, in every wind direction – prohibitive!
- Wind farm control changes the loads:
  - Turbine operation is changed
    - Rotor speed and pitch changes for axial induction control (reduced thrust mostly reduces loads)
    - Large yaw misalignments for wake steering (makes some loads higher, some lower)
  - Wake effects are modified
    - Increased wake velocities increases some mean loads
    - Reduced wake turbulence reduces fatigue loads generally
    - Changes in partial wake immersion affect asymmetric rotor loads (different loads affected in different ways)
  - The extent to which individual turbines are 'controlled', 'wake-affected' or both changes with wind direction
- Overall effect on lifetime fatigue is very complicated
  - Depends on position in farm, wind rose, and is different for different loads

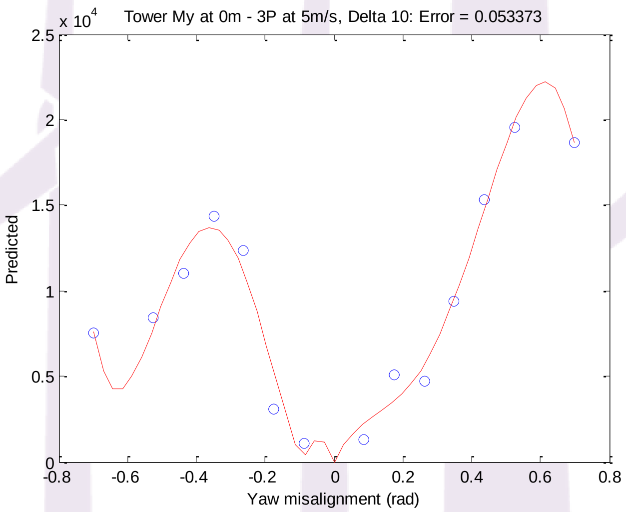
How to model these loads?

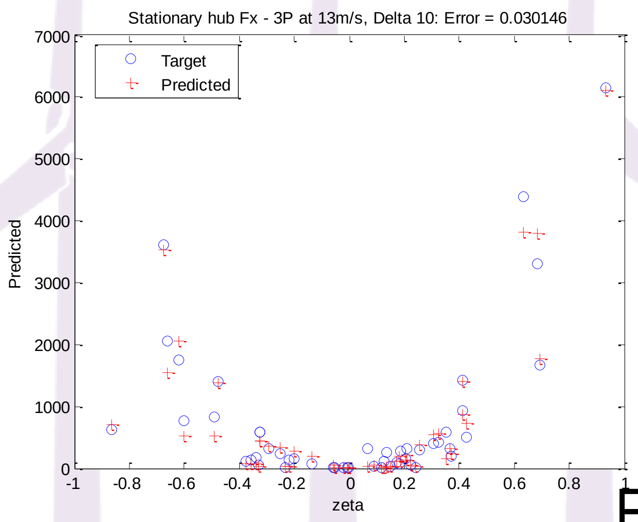
- **Current approach: Interpolate DELs from Fatigue Loads Database – many thousands of 10-minute dynamic simulations using *Bladed*, covering a multi-dimensional hypercube of conditions:**
  - Wind speed
  - Turbulence intensity (currently the only way to account for wake effects)
  - Wind shear
  - Yaw misalignment (for wake steering control)
  - "Power delta" (thrust reduction setting for axial induction control)
- **Single wake effects can be modelled in *Bladed* but database would require 3 or 4 more dimensions:**
  - Centreline offset (horizontal, vertical), centreline deficit, wake width
  - … but still wouldn't account for wake meandering and propagation dynamics, multiple wake superposition effects, etc.
- **New approach:**
  - Short targeted simulations to identify deterministic load contributions from shear, yaw, partial wake, gravity, etc.
  - Fit simple empirical models to these results
  - Small number of stochastic simulations to identify transfer functions embodying the effects of turbulence and structural dynamics
  - Synthesis: simply combine deterministic and stochastic load contributions in time domain.
  - Deals with multiple wakes, meandering, etc. in a straightforward way

Deterministic effects

- Separately model the effects of wind shear, yaw, partial wake, gravity etc. on each load
- Identify effect on the 3P Fourier harmonics (also 0P where appropriate; could easily extend to 6P etc. but mostly small effects)
- Fit simple functions to predict amplitude and phase of Fourier harmonics as a function of the driving effect



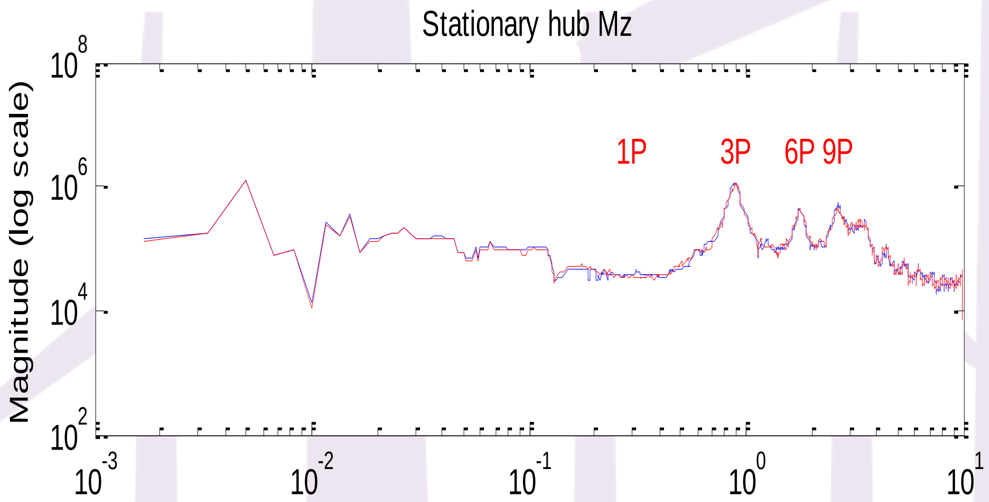




Stochastic effects

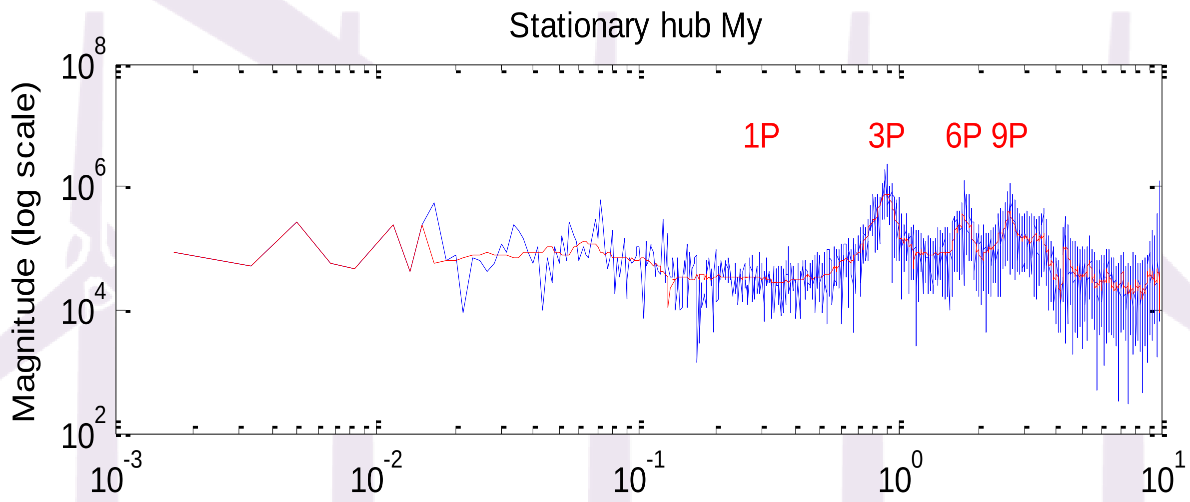
- Calculate transfer function from the hub longitudinal wind speed to each of the loads (with deterministic effects removed)
- Repeat for each wind speed (and thrust setpoint for axial induction)

Largely independent of turbulence



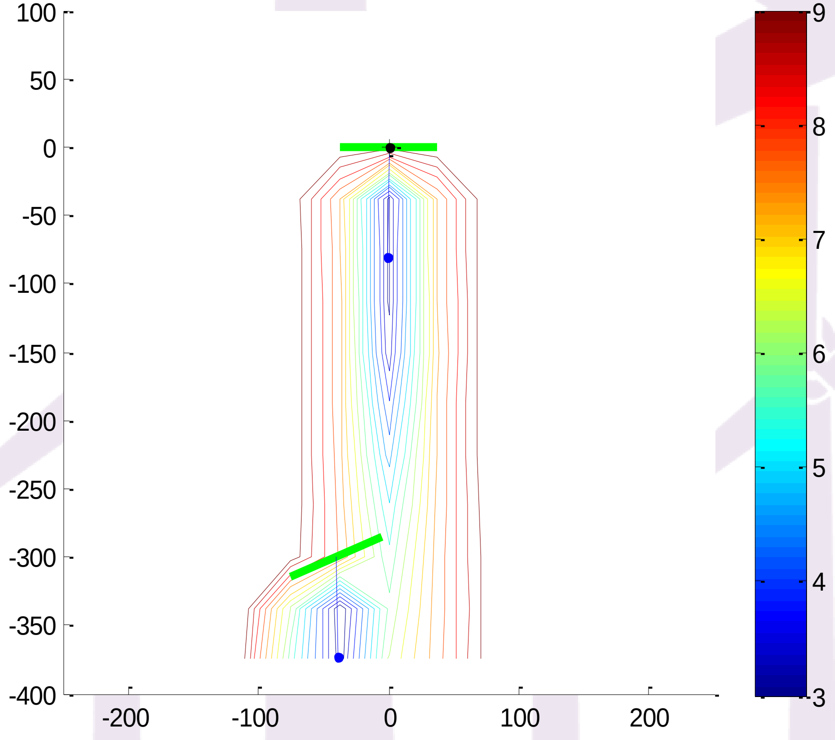
10% TI (blue), 20% TI (red)

Apply filtering to the magnitude

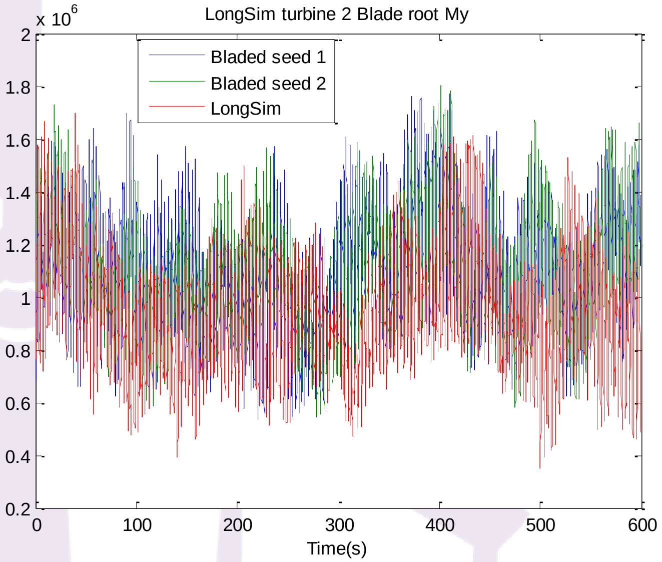


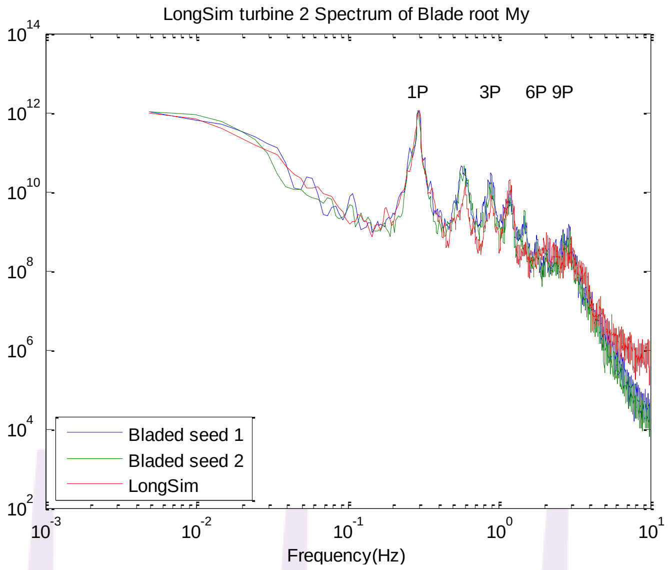
Comparison to Bladed

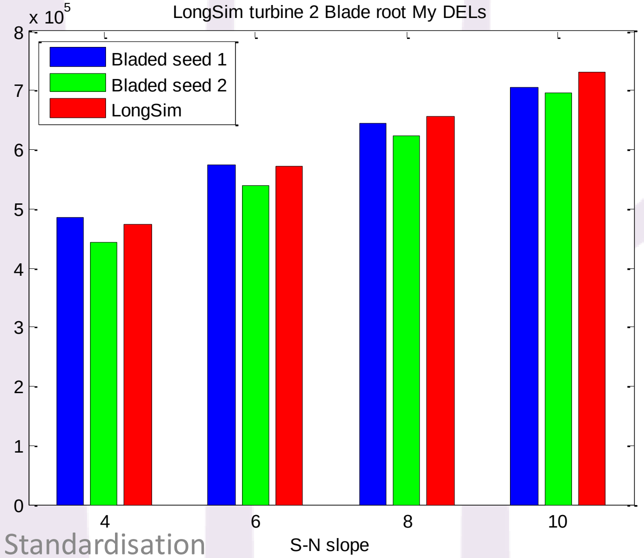
- Yawed turbine in partial wake with wind shear



Blade root bending moment:

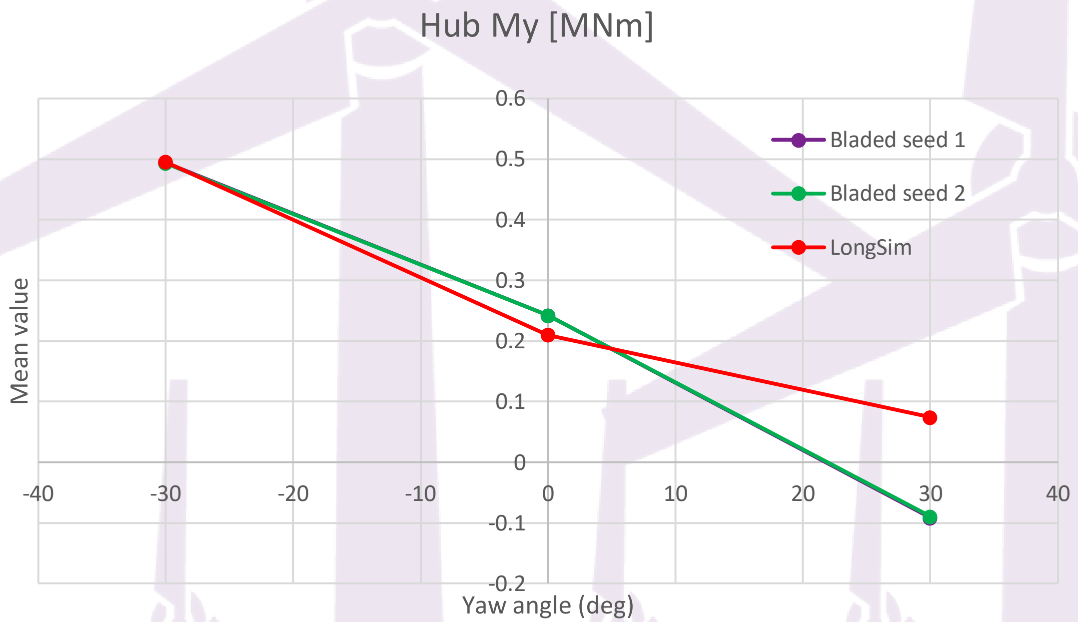


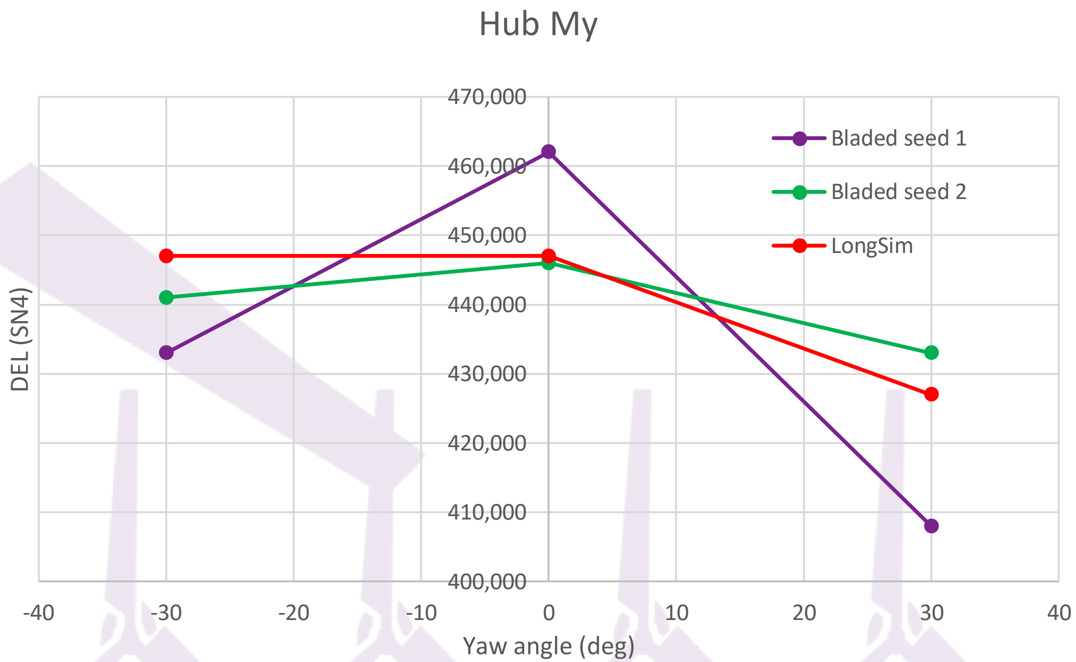




- Spectrum and DELs are well predicted!

Example: effect of yaw misalignment
Nodding moment





- Mean is increases with negative yaw, decreases with positive yaw

  BUT

- Fatigue load highest at zero yaw
- Fatigue strongly affected by turbulence random seed

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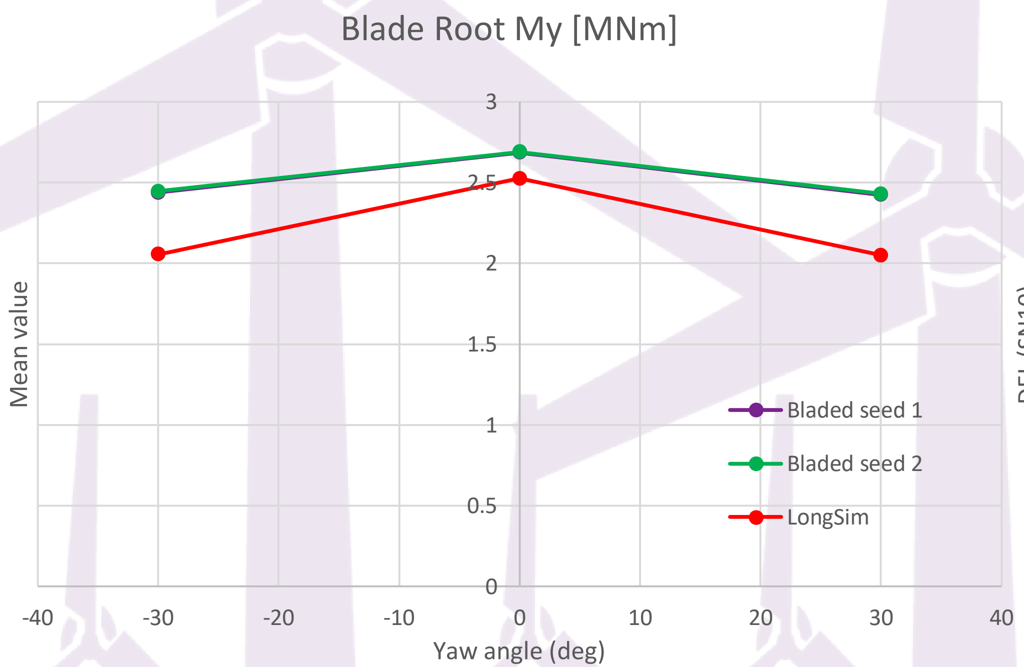
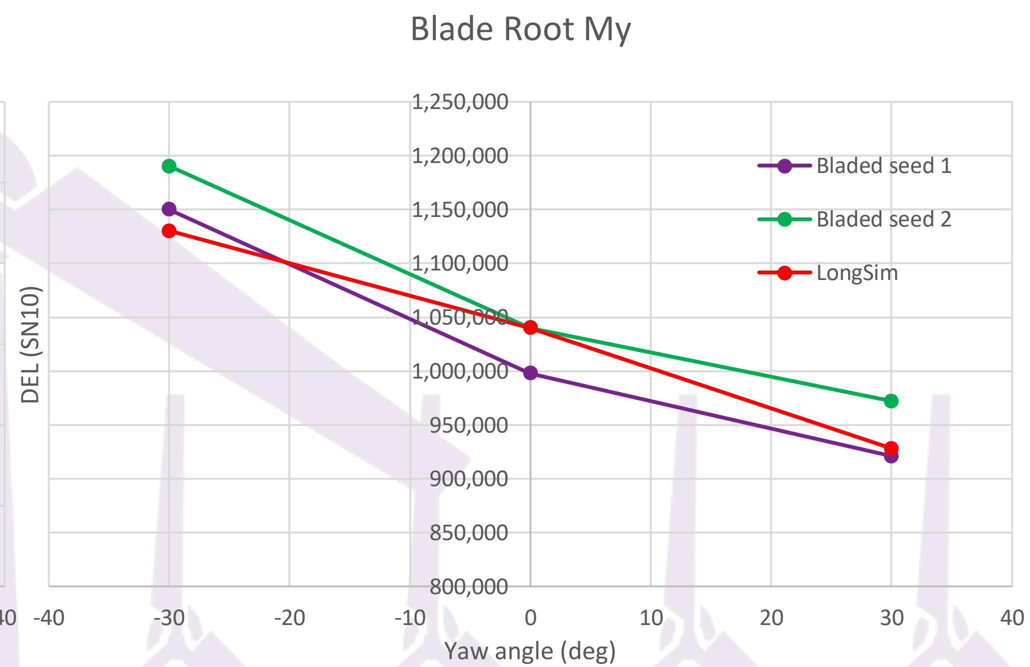
Example: effect of yaw misalignment
Blade root out of plane moment



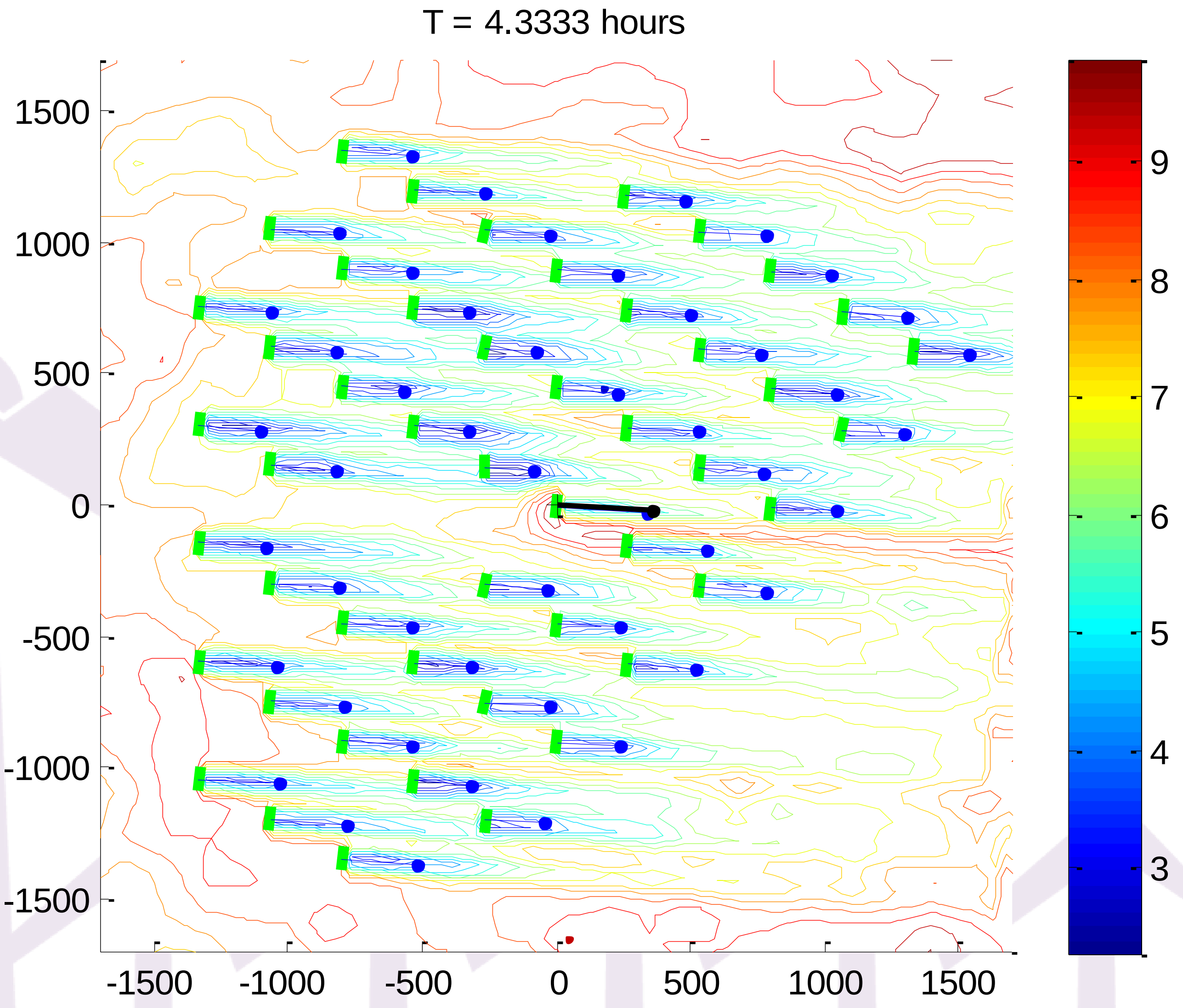


Other way round from nodding moment:

- Mean highest at zero yaw
- Fatigue increases with negative yaw, decreases with positive yaw

TotalControl project

- Lillgrund offshore wind farm
- 48 turbines of 2.3MW, close spacing
- Setpoint optimisations and dynamic simulations carried out
  - Wake steering
  - Induction control
- Ongoing: design of a field test for induction control
- Setpoints optimised for power only (ignoring loads)



Optimisation with loads (whole wind farm)

Illustrative example with axial induction control: Lillgrund, 222º direction, 9m/s

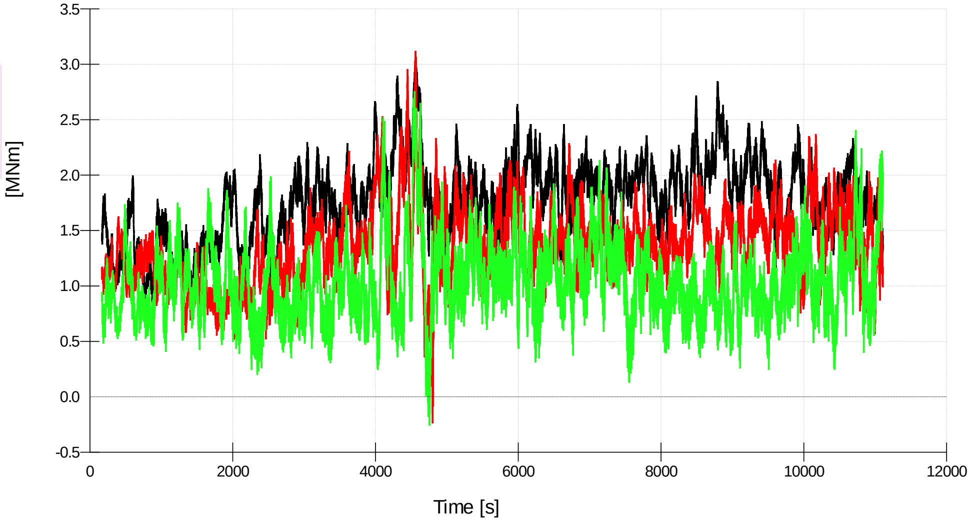
1. Power-only optimisation
   - Total power (100% weight)
2. Optimisation for Power and loads (arbitrary choice, for illustration)
   - Total power (90% weight)
   - Blade root My DEL Wöhler 10: **maximum** of any turbine (5% weight)
   - Tower base My DEL Wöhler 4: **sum** over all turbines (5% weight)

CHANGE:	Power only optimisation	Power and loads
Power (total)	+1.71%	+1.35%
Blade root fatigue (max)	-34.81%	-35.50%
Tower base fatigue (total)	-12.56%	-10.31%

- Optimising for power only already reduces those two load measures very significantly!
- Further reduction on max blade root fatigue is difficult: trade-off against the other two measures (only an illustration!). Probably better to remove blade root weighting, as that's already much reduced.

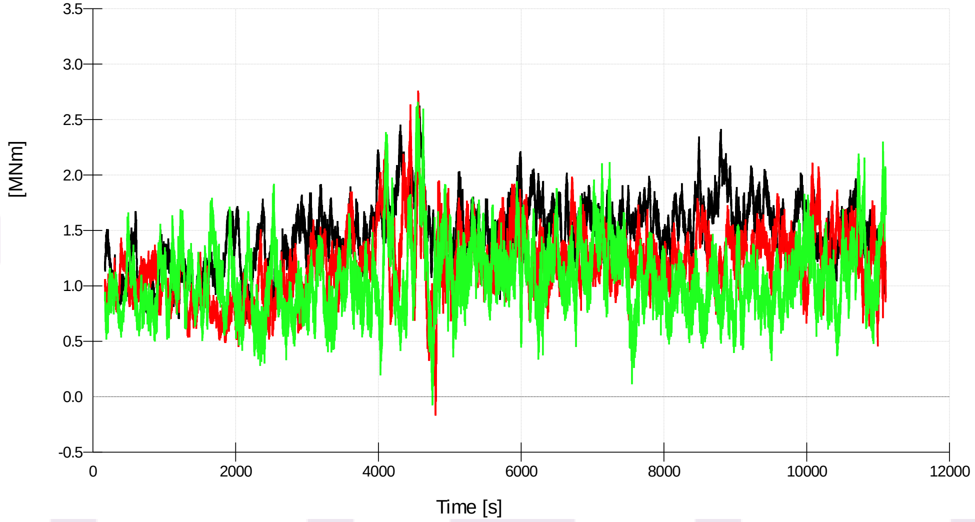
Time-domain simulation with loads

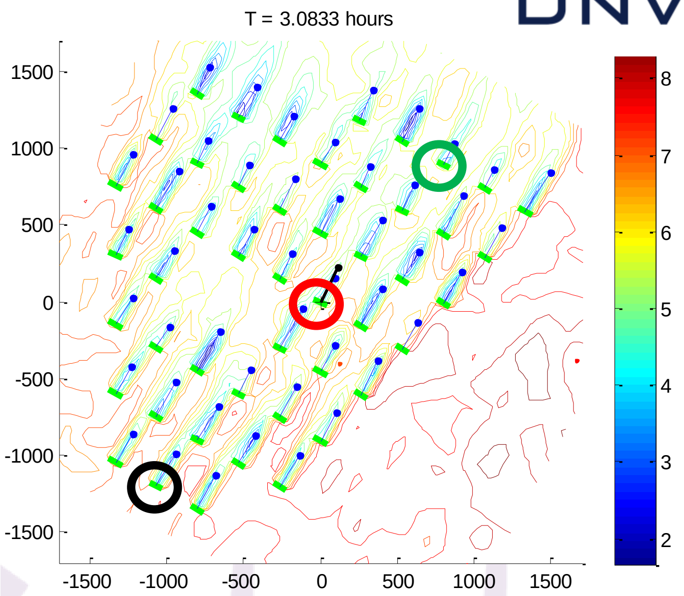
Base case – no control



	Base case		Control on	
	Mean	Std Dev	Mean	Std Dev
D-08	1.77	0.35	1.47	0.30
D-04	1.37	0.35	1.20	0.30
D-01	1.03	0.34	1.06	0.32

With axial induction control active





- 3-hour simulation
- Wind field created from SCADA wind conditions
- Example: blade root bending moment from three turbines shown

Conclusions

- Surrogate loads model: accounts for wake effects in detail
- Good agreement with Bladed for fatigue loads
- Allows loads on all turbines in the farm to be evaluated
- Much quicker than aeroelastic simulation
- Relatively small number of training simulations
- Allows setpoint optimisation to include loads
- Allows time-domain wind farm simulation including loads

Acknowledgements

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- No. 727477 CL-Windcon, website: www.clwindcon.eu
- No. 727680 TotalControl, website: www.totalcontrolproject.eu
- No. 857844 FarmConners, website: www.windfarmcontrol.info

Thank you for your attention!

Source: TU Delft – FLORIS simulation B.M. Doekemeijer et al.

Further Questions?

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