Evolution of load simulation methods in a systems engineering perspective

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with input from:
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Leonardo Bergami
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Torben Larsen
and others
Selected highlight in the model development

- Simplified load paradigm
- Load basis from measurements

Timeline:
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015
Simplified load basis

- From 300 N/m^2 to standardized load spectrum based on measurements

- Combination of stochastic and deterministic loads
- The importance of frequency coincidence
Selected highlight in the model development

- Simplified load paradigm
- Load basis from measurements
- ‘real’ turbulence models
- Industrial use of aeroelastic models

- Aeroelastic models (DYNAWECS, co-rotational 1981)
- Few DOF Aeroelastic models (FLEX4)
- Frequency domain models
- FEM based Aeroelastic models (HAWC)

Timeline:
- 1985
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- 2015
Industrial use of aeroelastic models

- The industry matured
- Turbines grew – cost and safety became issues
- Models developed from separate aerodynamics and load tools to combined aeroelastic tools
- The need for standardization was recognized

- The triggering points in the model development became partly the development of the turbine technology, partly issues experienced in the field
- Depending on the task at hand, the fidelity level needed varies
Selected highlight in the model development

1985
- Simplified load paradigm
- Frequency domain models
- Aeroelastic models (DYNAWECS, co-rotational 1981)

1990
- Load basis from measurements
- Few DOF Aeroelastic models (FLEX4)

1995
- ‘real’ turbulence models
- Stall induced vibration – aer + structure
- Large blades - Non-linearities
- Multi body codes

2000
- FEM based Aeroelastic models (HAWC)
- Focus on control and grid requirements
- Dedicated stability tools

2005
- More detailed aerodynamics – link to CFD
- Offshore modules included – monopiles
- Detailed wake models

2010
- Link to detailed component design: superelements

2015
- Offshore modules included – jackets + floating str.

- Industrial use of aeroelastic models
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- Industrial use of aeroelastic models
State of the art aeroelastic modelling

- Handling of non-linear large deflections
- Various aerodynamics models fully coupled to the structural model (from BEM to CFD)
- Fully integrated turbine controller
- Integrated support structure modelling
- Offshore modelling capabilities
- Option for separate frequency domain analysis of modal characteristics

HAWC2 model developed as part of the OC4 project  DTU-I-0240(EN)
**Typical full-IEC load setup for design**

All possible situations are simulated

Various combinations of mean wind and turbulence

...and fault conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>WSP</th>
<th>Wdir</th>
<th>Gust</th>
<th>Fault</th>
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<tbody>
<tr>
<td>DLCxxx</td>
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<td>Start-up at four diff. times</td>
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<td>Start-up in EDC</td>
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<tr>
<td>DLC41</td>
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<td>Shut-down at site</td>
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<td>-20/20</td>
<td>0.11</td>
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<td>Vmaint</td>
<td>-8/8</td>
<td>NTM</td>
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</tbody>
</table>

In total 1-2000 simulations onshore

**Will we continue to see development towards more complex models and more requirements?**

Yes, but for Systems Engineering the answer could be different
How simple can a load model be?

• Sometimes we need a fast estimate on main load signals – typical for product scoping, conceptual evaluation or for systems engineering/optimization

• How low can we go?

• **Rated power** and **diameter** combined with some engineering experience?
Thrust and power coefficients

\[ C_t = 4a(1 - a)F \quad C_p = 4a(1 - a)^2F \]
Power, thrust force and its gradient

\[ P = \frac{1}{2} \rho A V^3 C_p \]

\[ T = \frac{1}{2} \rho A V^2 C_t \]

\[ \frac{dT}{dV} \approx \frac{T_{i+1} - T_i}{V_{i+1} - V_i} \]
Flapwise moment and its gradient

Assuming triangular blade load distribution:

\[
M_x \approx \int_0^R \frac{2}{3} \frac{T}{R^2} r^2 dr = \frac{2}{9} TR
\]

\[
\frac{dM_x}{dV} \approx \frac{M_{x,i+1} - M_{x,i}}{V_{i+1} - V_i}
\]
From turbulence to load variation

\[ \sigma_{M_x} \approx \sigma_{V} \frac{dM_x}{dV} \]
From std. dev. of loads to extreme loads

![Graph showing Flap moment vs Wind speed with Flap, FlapMax, and FlapMin data points marked]
From std. dev. of loads to STEL

Assuming that flapwise moment has a dominating 1P component with period $T_{1P}$ and adjusting its range with the factor $a_\sigma$:

$$R_{eq} = \left(2a_\sigma \sigma_{M_x} \frac{m}{T_{1P}} \right)^{\frac{1}{m}}$$

**STEL:**

$$R_{eq} = \left(2a_\sigma \sigma_{M_x} \frac{m}{T_{1P}} \right)^{\frac{1}{m}}$$
Simplified model and full model

<table>
<thead>
<tr>
<th></th>
<th>Full</th>
<th>Simple</th>
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<tbody>
<tr>
<td>Maximum flap</td>
<td>22435</td>
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<td>Life time fat. flap</td>
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<td>Maximum tower</td>
<td>168500</td>
<td>123300</td>
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<tr>
<td>Life time fat. tower</td>
<td>61280</td>
<td>61088</td>
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Needed modelling level depends on the task
Development drivers and future perspective

Development drivers
- Turbine technology
- System requirements – e.g. grid requirements, flexibility, etc.
- Design optimization/design to limit – experience from field

Future perspectives
- One-system-design-process: integration of component and ‘system’ design
- Further coupling between aero-elastic and electrical modelling
- Inflow modelling – further development of turbulence models (and other external conditions)
- Validation methods, formal quantification of success criteria
- For different tasks we need different fidelity levels – both simple fast robust models but also high fidelity models with all details