Campbell Diagram and Blade Stability Analysis

Frequency domain analysis

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Campbell Diagram in 4.8

Campbell Diagram changes with New Aerodynamics (4.8)

- Linear System:

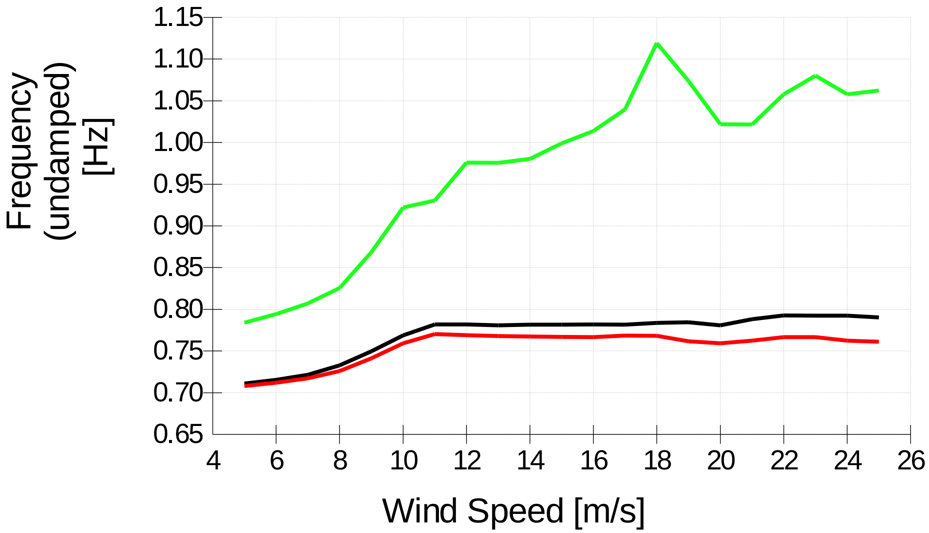
$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$
$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u}$$

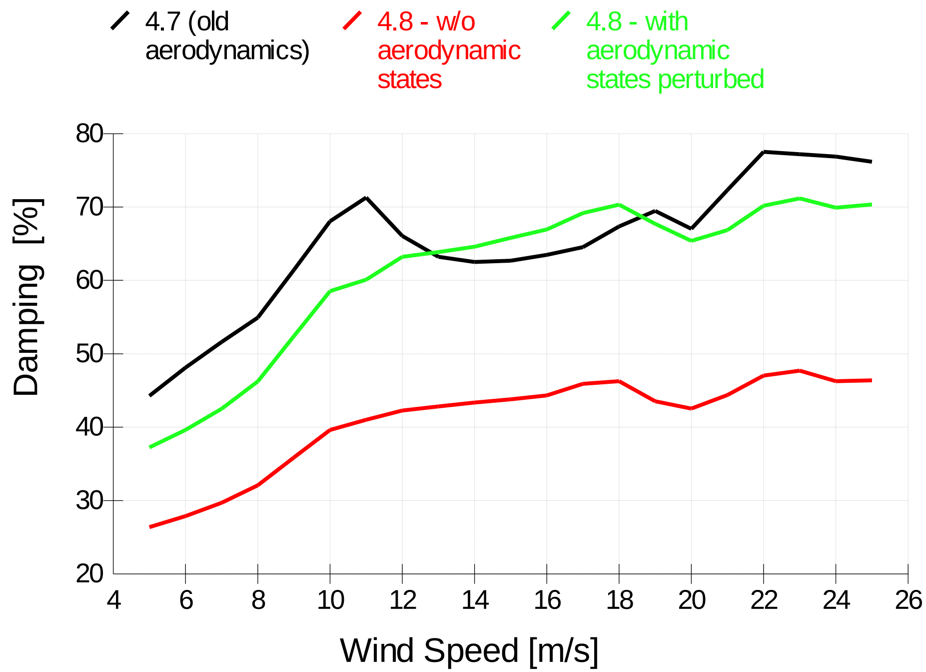
- In aeroelastic model, the state vector $\boldsymbol{x}$ is mostly two types:
  - Elastodynamic (structural modes etc…)
  - Aerodynamic (dynamic stall, wake etc…)
- In the time domain, these must be integrated.
- In the **frequency domain**, these must be **linearised**.
- Campbell diagram is an analysis of the $\boldsymbol{A}$ matrix:

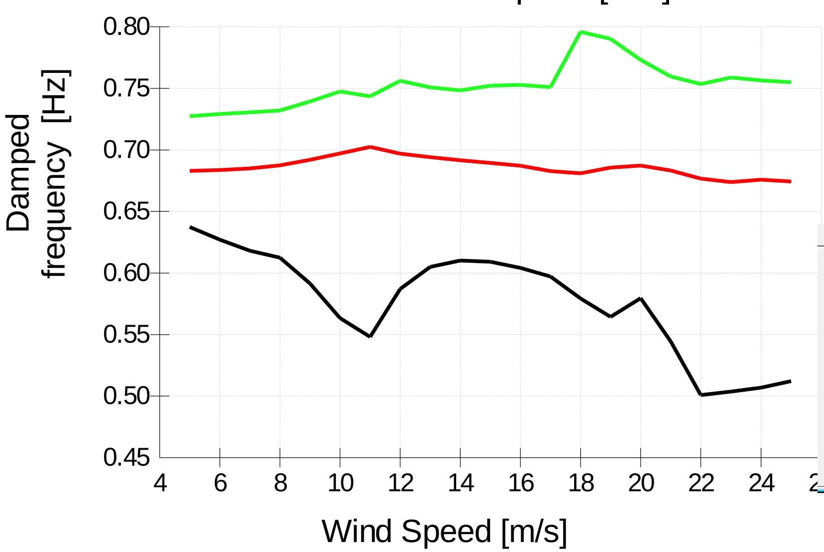
$$\begin{pmatrix} \dot{\boldsymbol{q}} \\ \ddot{\boldsymbol{q}} \\ \dot{\boldsymbol{z}} \end{pmatrix} = \begin{pmatrix} 0 & \boldsymbol{I} & \boldsymbol{T}_{qz} \\ \boldsymbol{M}^{-1}\widetilde{\boldsymbol{K}} & \boldsymbol{M}^{-1}\widetilde{\boldsymbol{C}} & \boldsymbol{T}_{\dot{q}z} \\ \boldsymbol{T}_{zq} & \boldsymbol{T}_{z\dot{q}} & \boldsymbol{T}_{zz} \end{pmatrix} \begin{pmatrix} \boldsymbol{q} \\ \dot{\boldsymbol{q}} \\ \boldsymbol{z} \end{pmatrix} + \boldsymbol{B}\boldsymbol{u}$$

- The **old aerodynamics was loosely coupled** to the structural model and its **states were not analysed**.

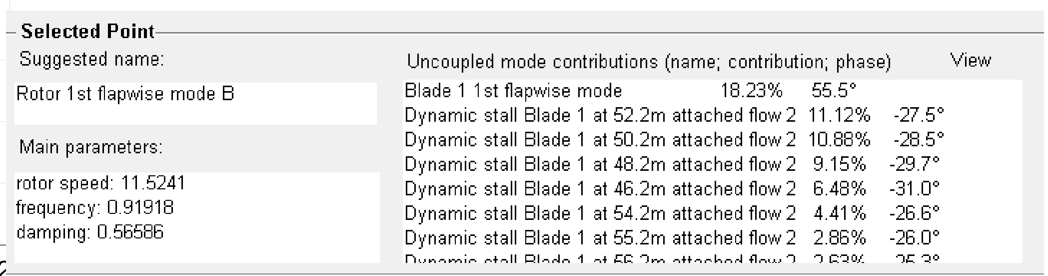
What effect do these aerodynamic states have? – 1st flapwise





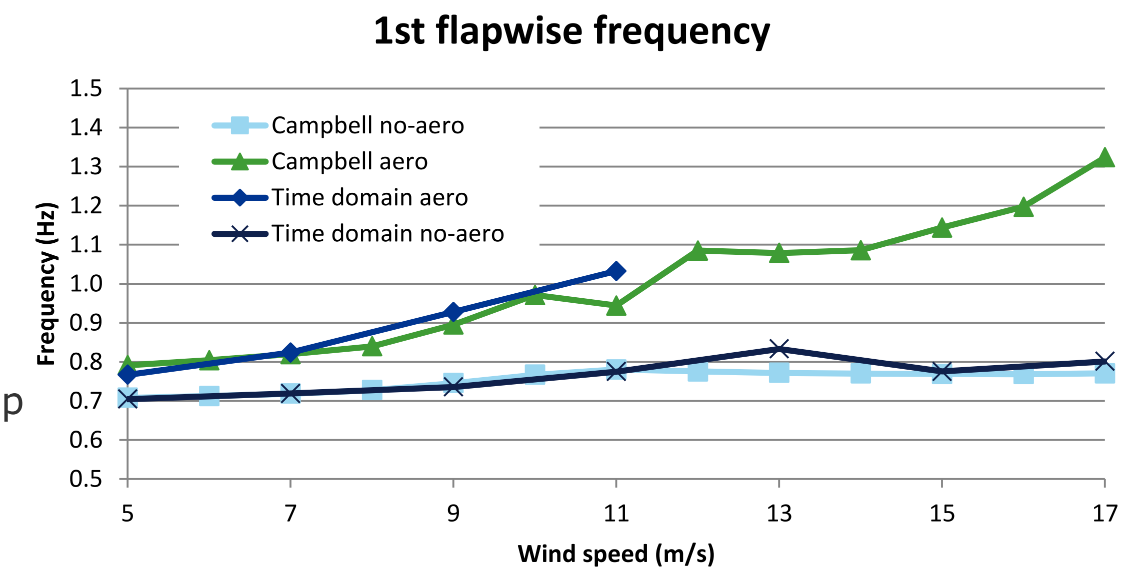


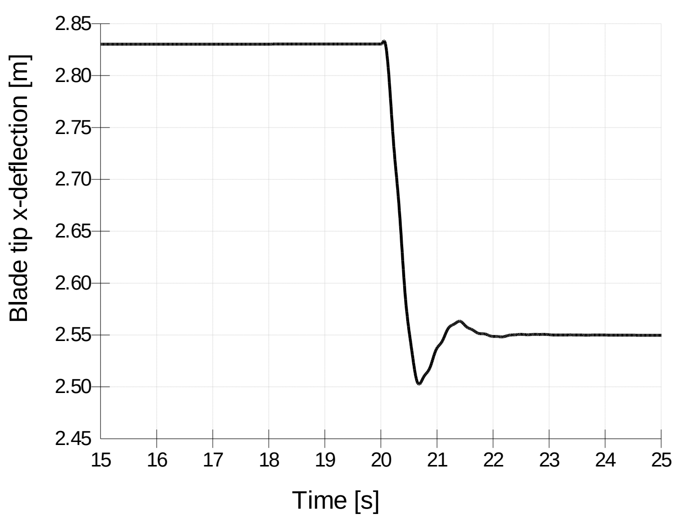
At 16m/s:

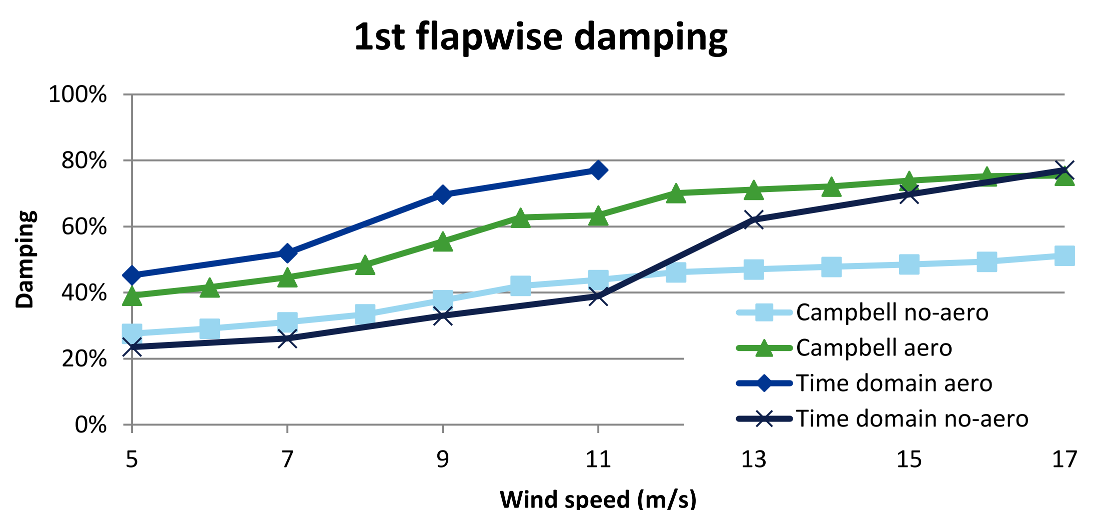


Comparison with time domain step response

- Due to high damping, flapwise modes not visible in spectral analysis.
- Apply out-of-plane loading and remove it instantly.
- Use system identification to measure the 2nd order decay of tip deflection.







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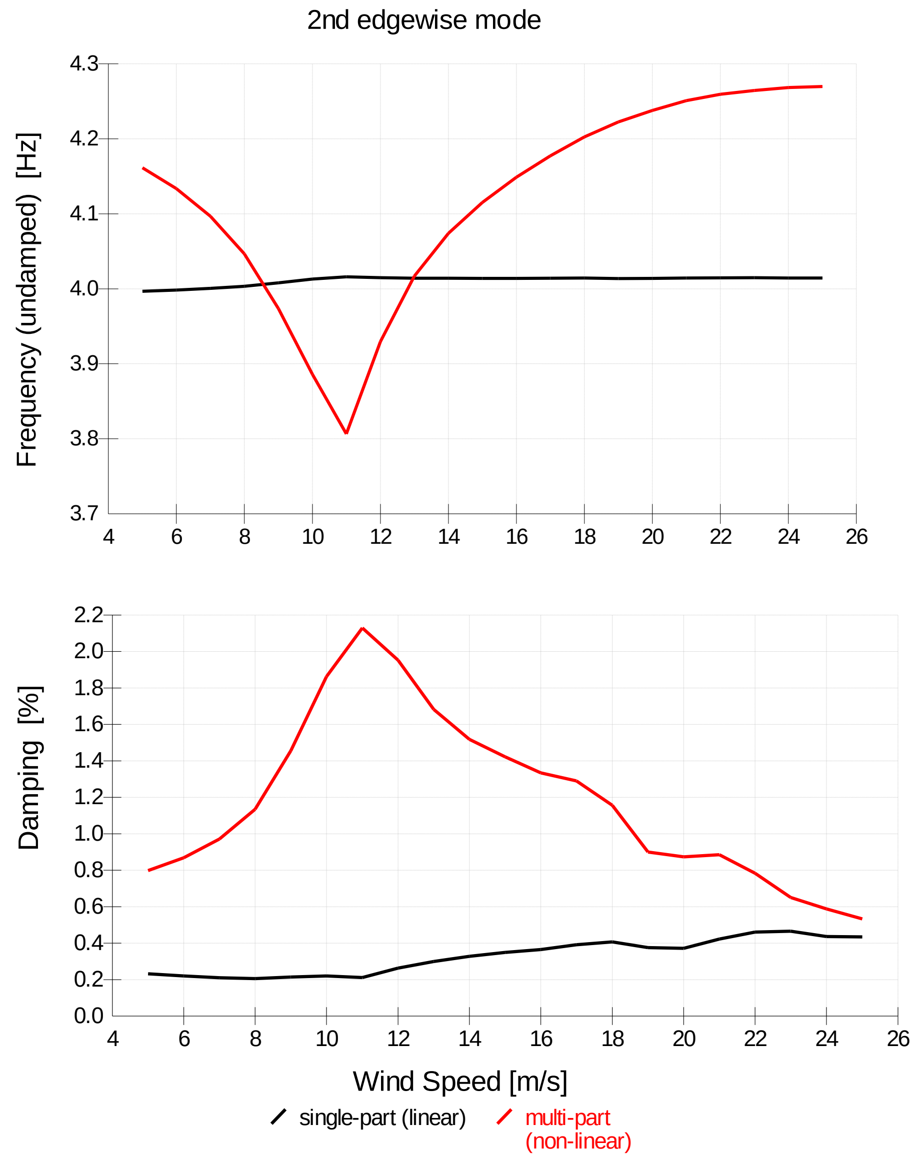
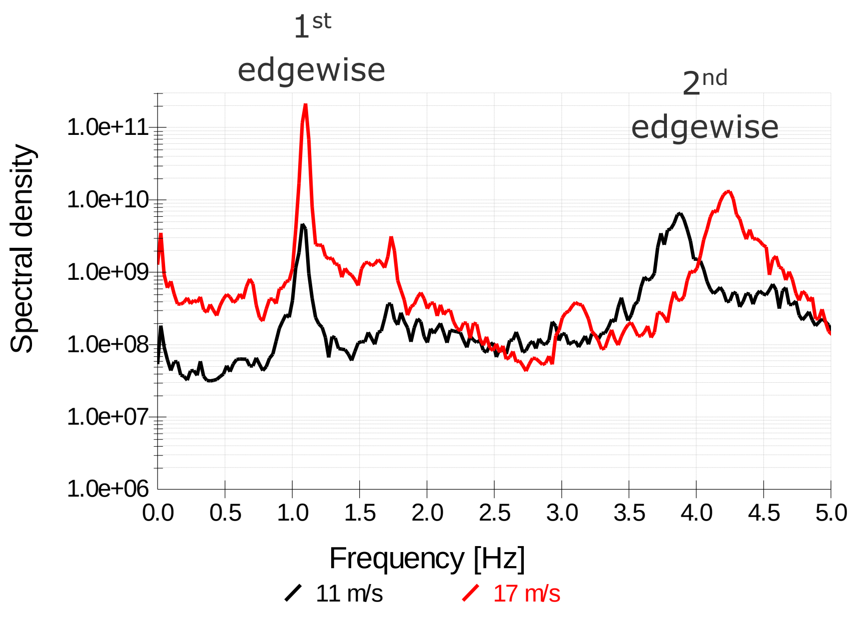
Edgewise modes – multi-part blade

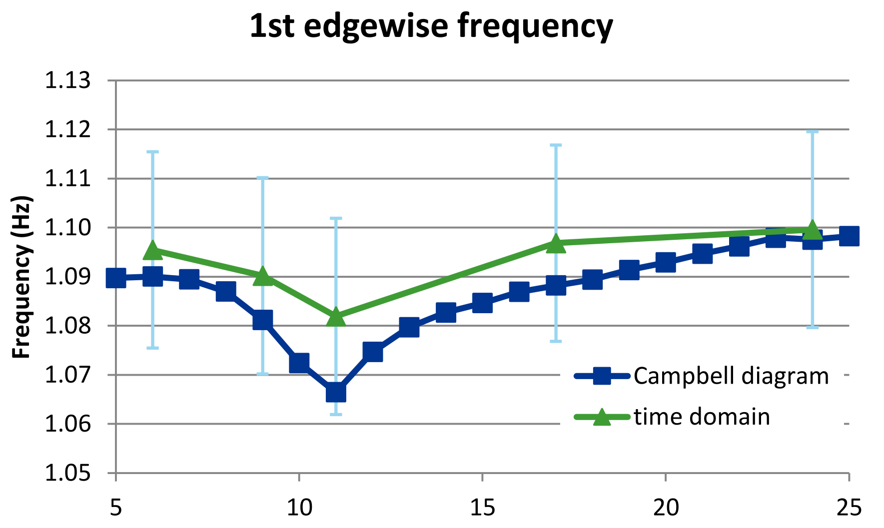
- Non-linear modelling changes significantly the steady-state deflection of the blade.
- The edgewise whole blade mode shapes also have a highly varying shape (e.g. torsional component reverses sign)
- This has a dramatic impact on frequency and damping.
- Analysing dynamic stall states also has some impact but much less significant.

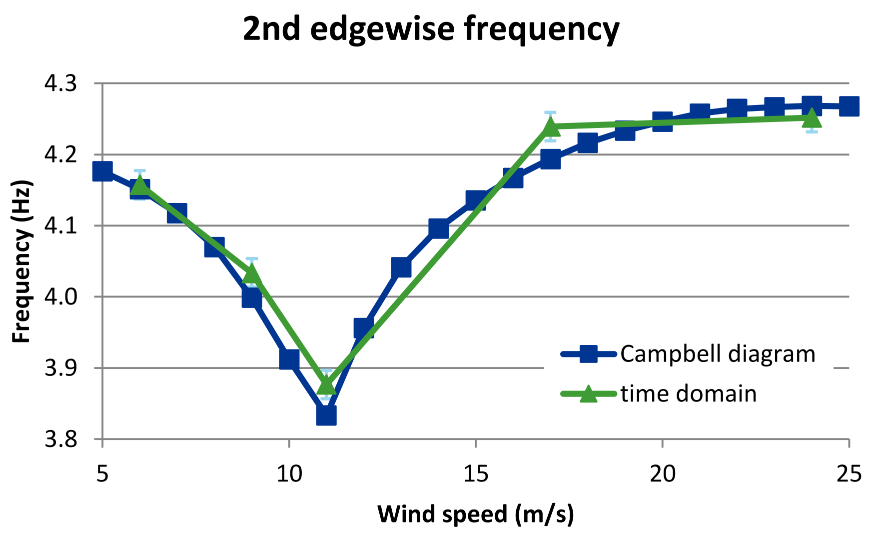


Edgewise modes – time domain verification

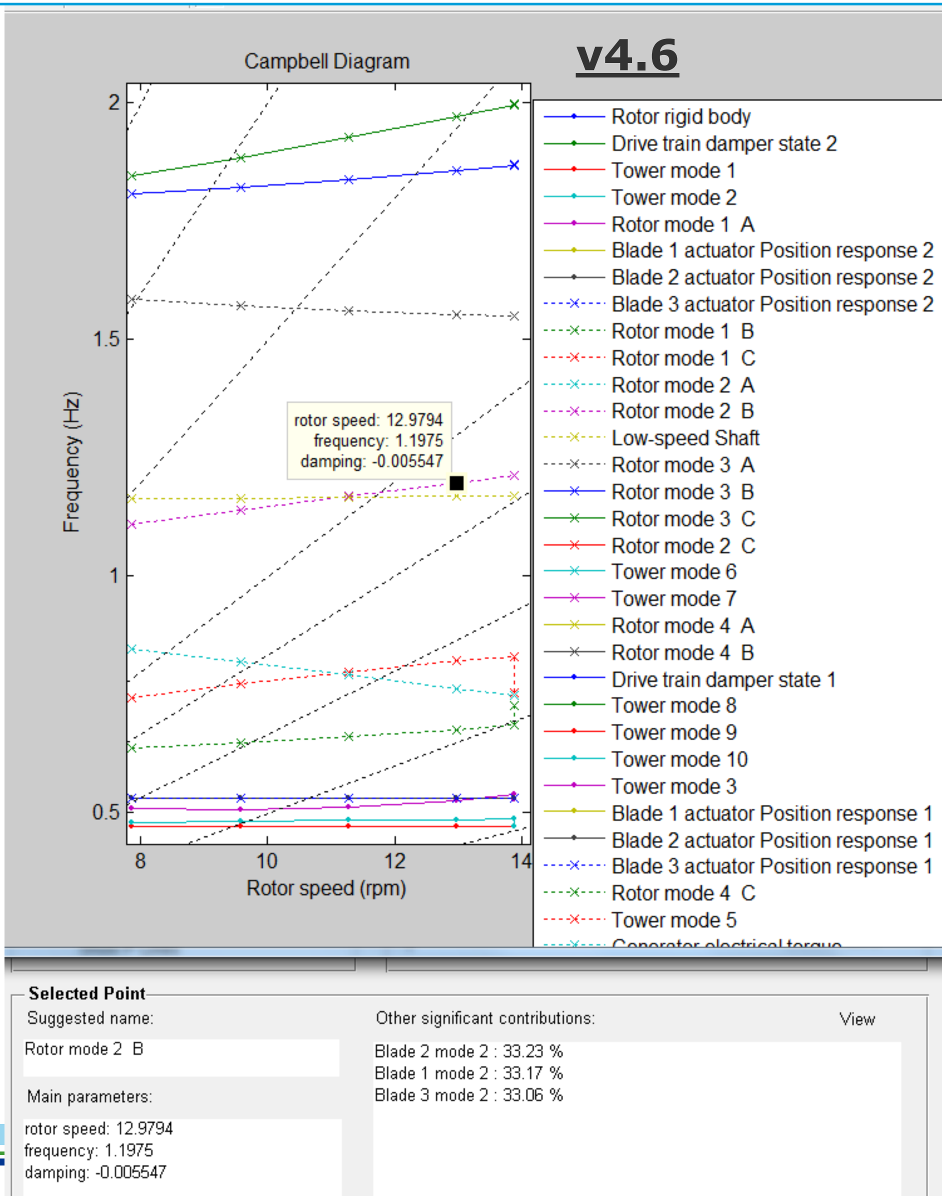
- Performed steady-state runs with high-pass filtered turbulent wind at each wind speed.
- In spectral analysis of blade root Mx or Fy load, frequency of edgewise peaks are easily identified.

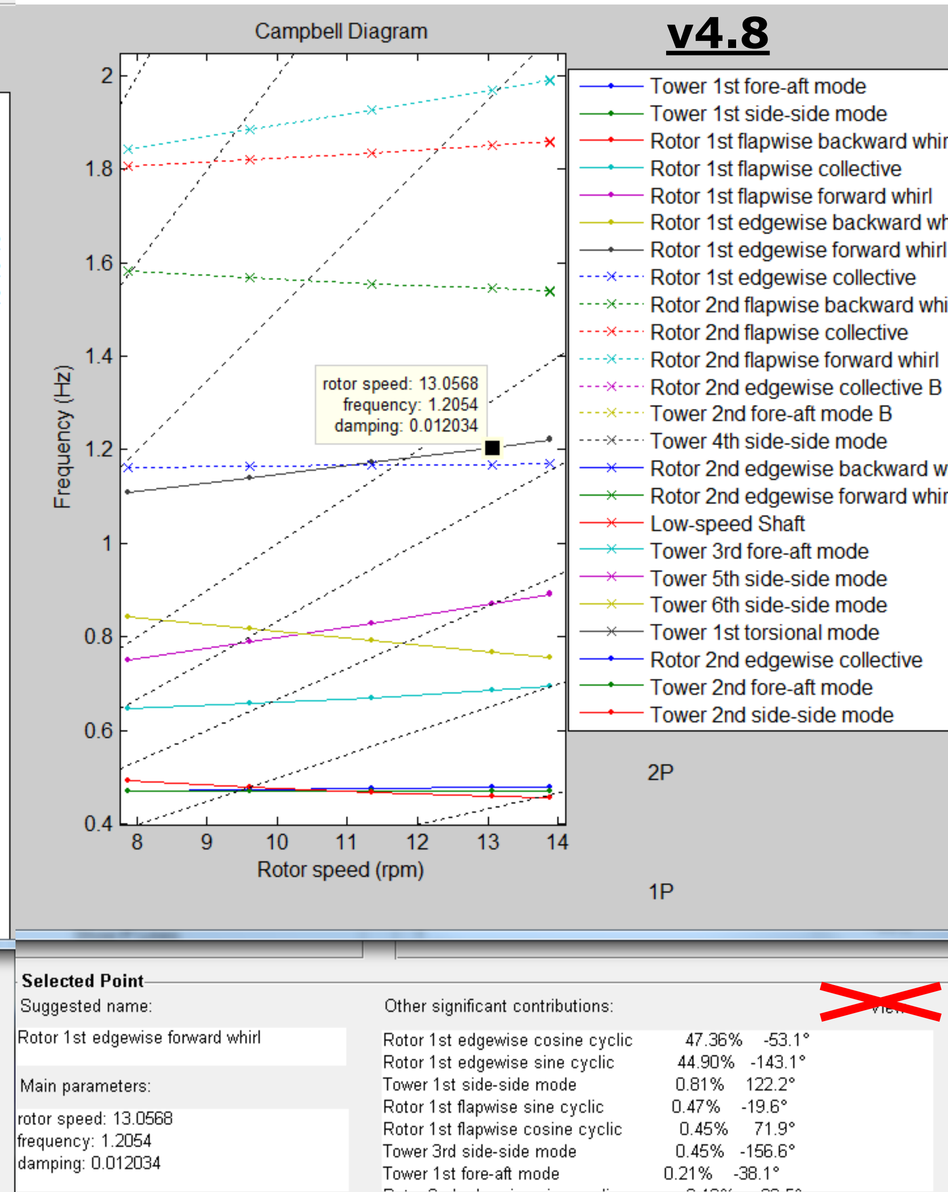






Campbell Diagram Naming Improvements





Blade Stability Analysis

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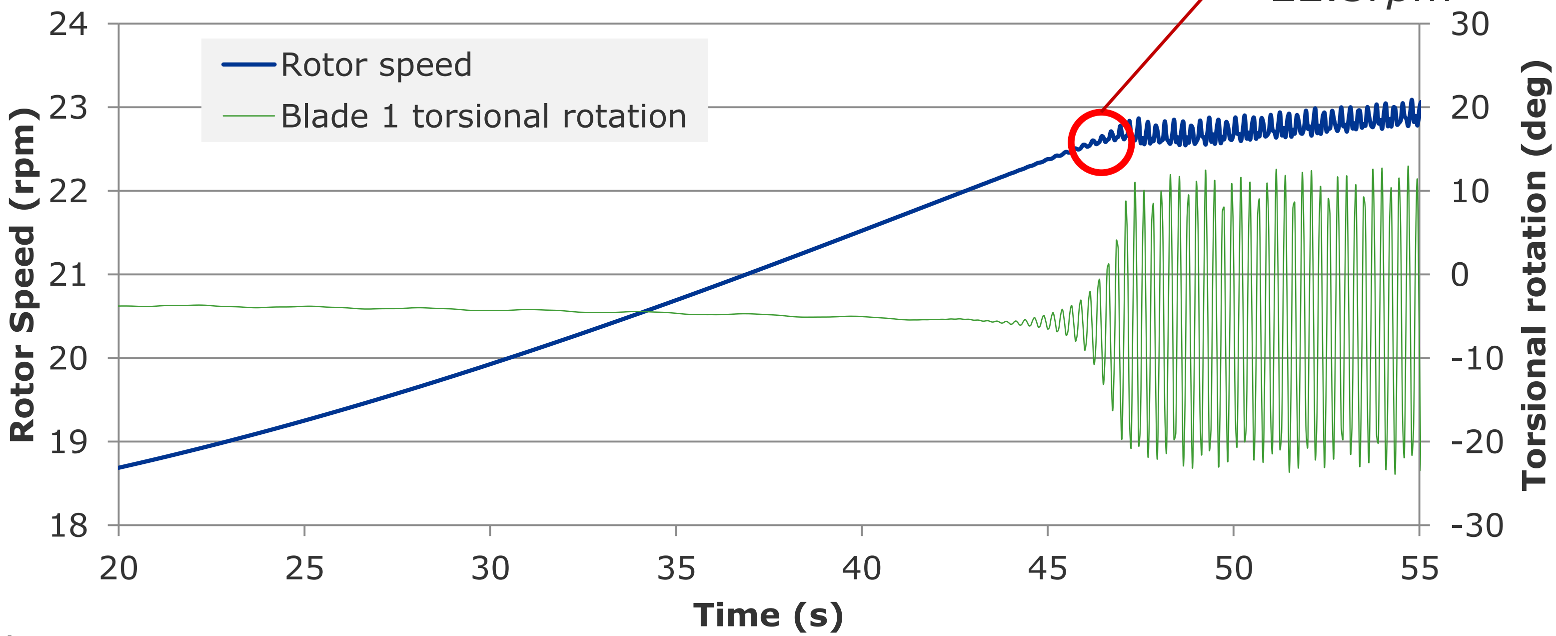
Time domain flutter analysis (all Bladed versions)

- Idling rotor, no generator torque; wind speed ramped from zero to high values
- Instability (flutter) observed through large oscillations in blade deflections above certain rotor speeds
- Downsides
  – lack of insight into cause of instability
  – Sensitive to wind speed ramp rate

Flutter point at ~22.5rpm



Pre-requisites of Blade stability tool

Geometrically non-linear blade structural model

Aerodynamic model
- Linearisable
- Valid for large deflections

Eigensolver (LinearModel.dll)
- Numerically well conditioned with large number of states
- Reliable with large number of modes and in high wind speeds

Equilibrium search algorithm
- Works with large number of modes
- Works at high rotor speeds

Blade Stability Tool

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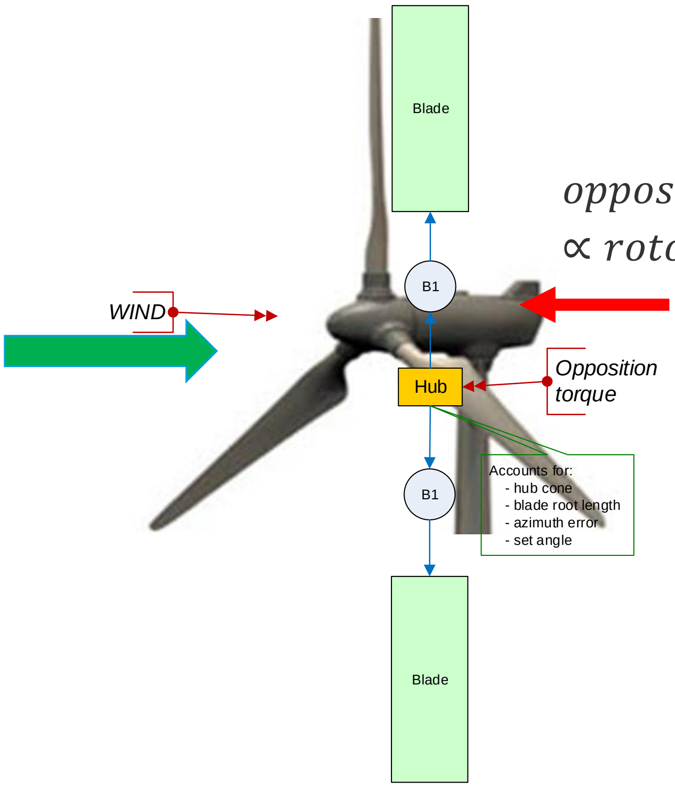
Types of Analysis

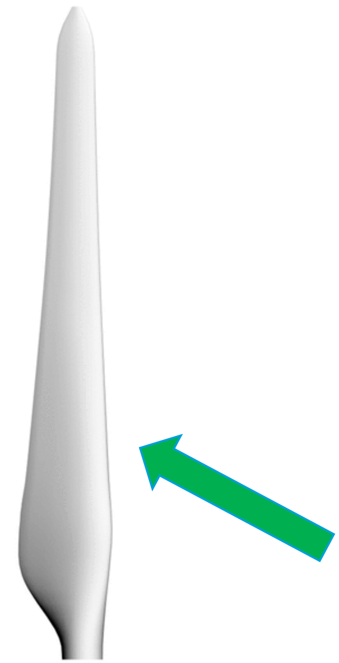
Tip-speed ratio tracking



$oppositon\ torque \propto rotor\ speed^2$

Rotor speed increases linearly as wind speed is increased

<u>Parked</u>



Loop over wind speeds.

Can use different yaw angles

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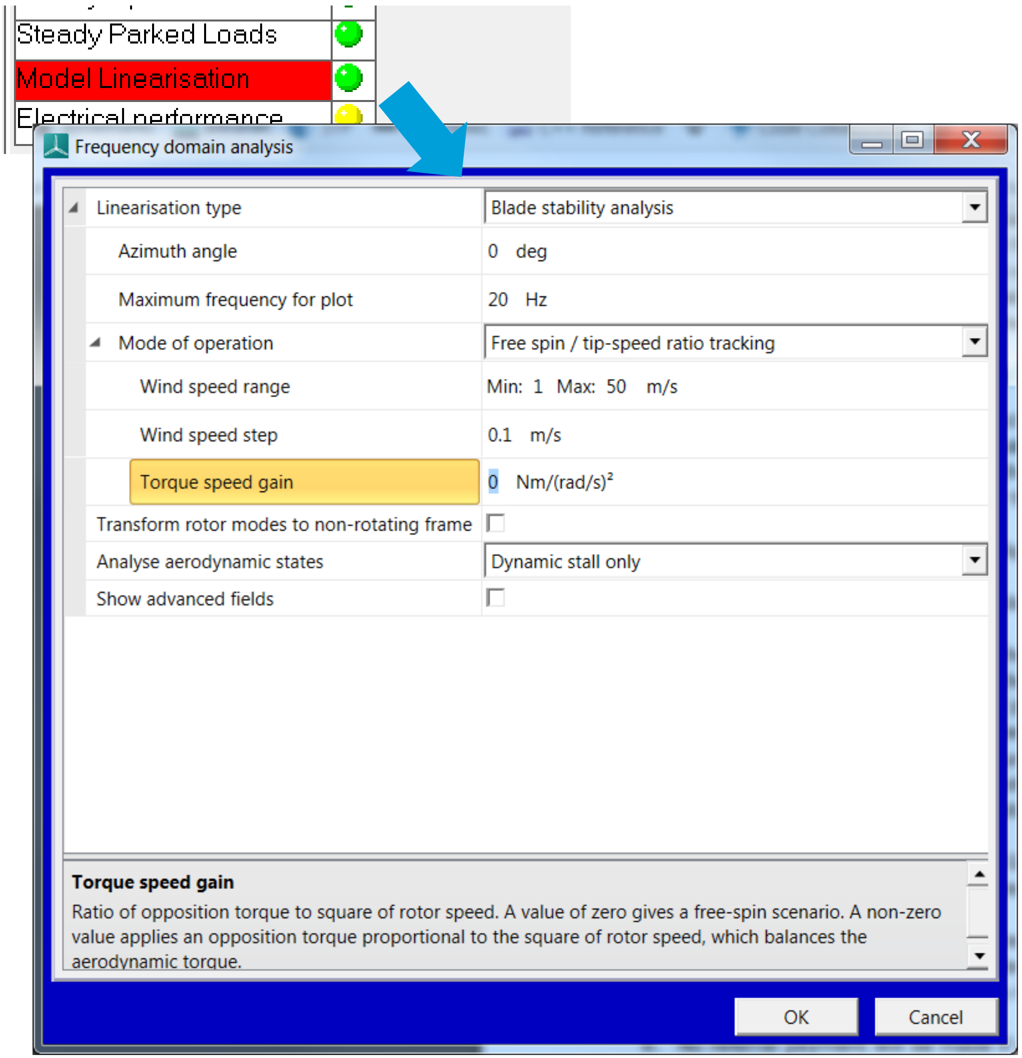
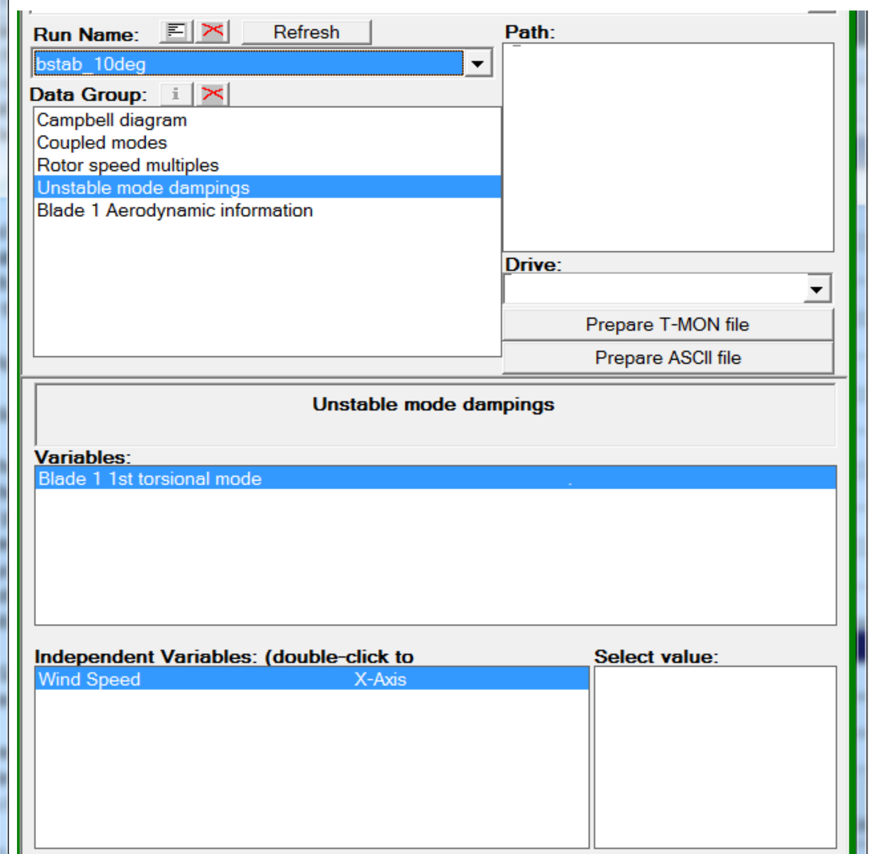
Blade Stability setup and results





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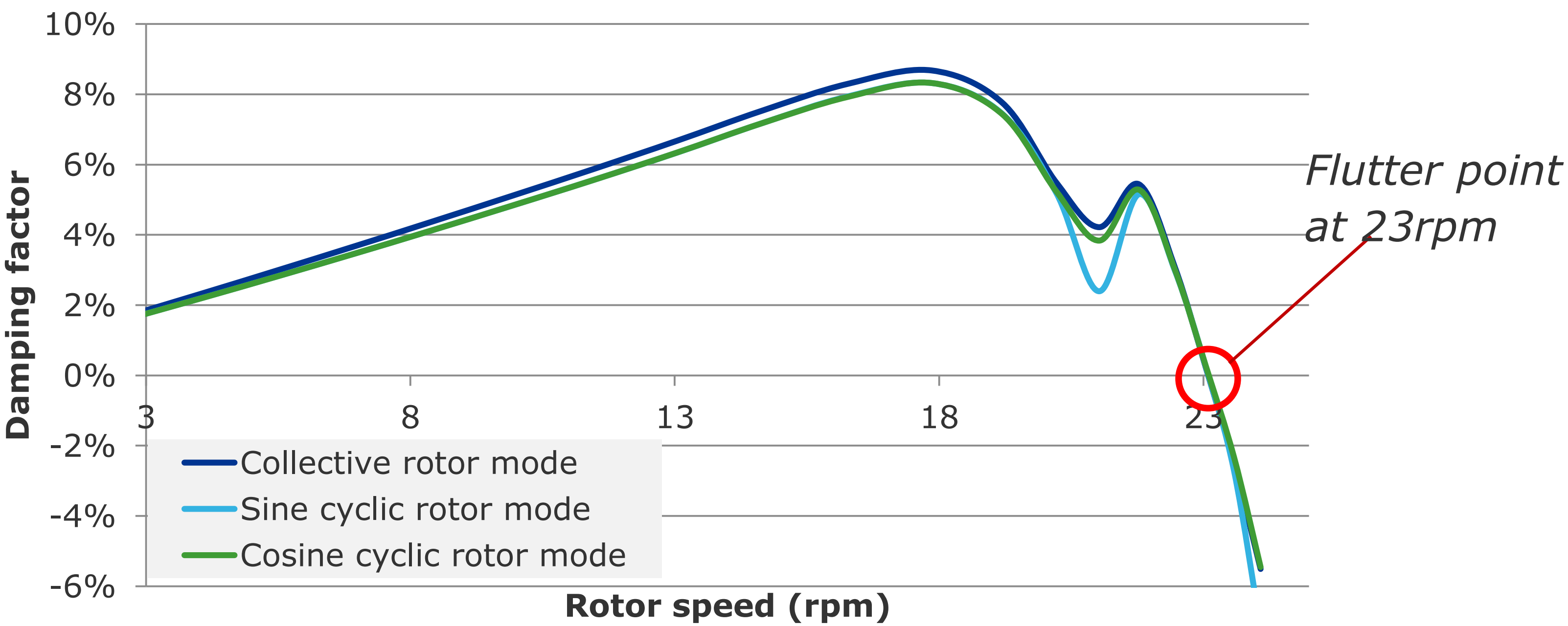
Blade Stability Analysis – TSR tracking

- Steady-state rotor speed and blade deflections determined at each wind speed.
- Model is linearised by perturbing all structural states (blade modes)
- Frequency, damping and mode shape calculated for all coupled modes.

- Provides **insight** into cause of instability (e.g. which modes are involved)



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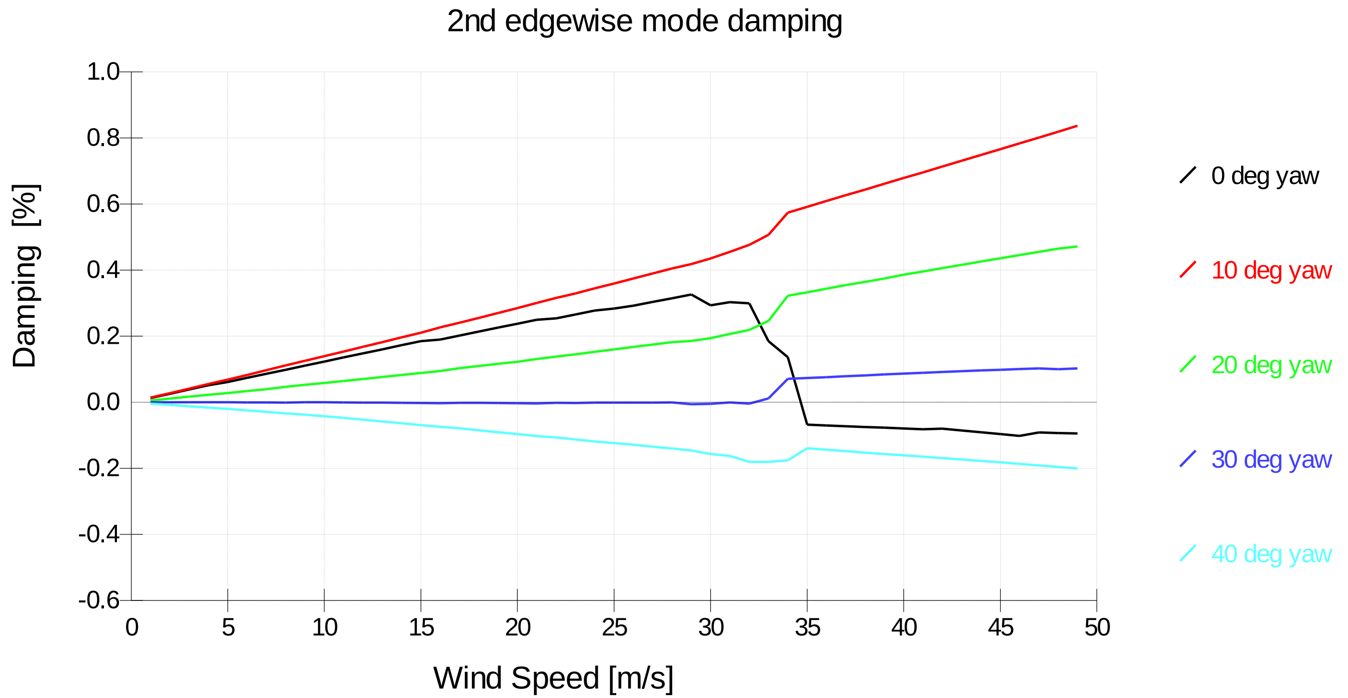
Blade stability – Parked analysis

- Damping of all coupled modes at different wind speeds & yaw angles
- Highly sensitive to aerofoil and other data
- Up to what angles of attack are dynamic stall models valid?
  - Results at high angles of attack should be treated with scepticism



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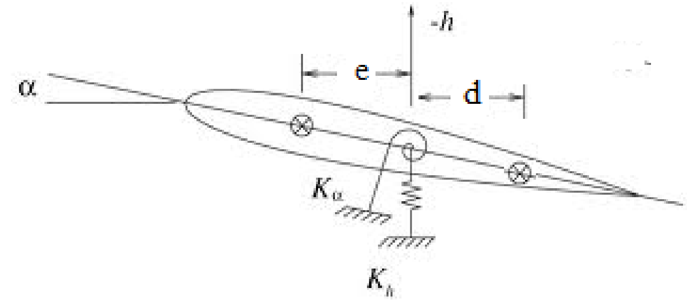
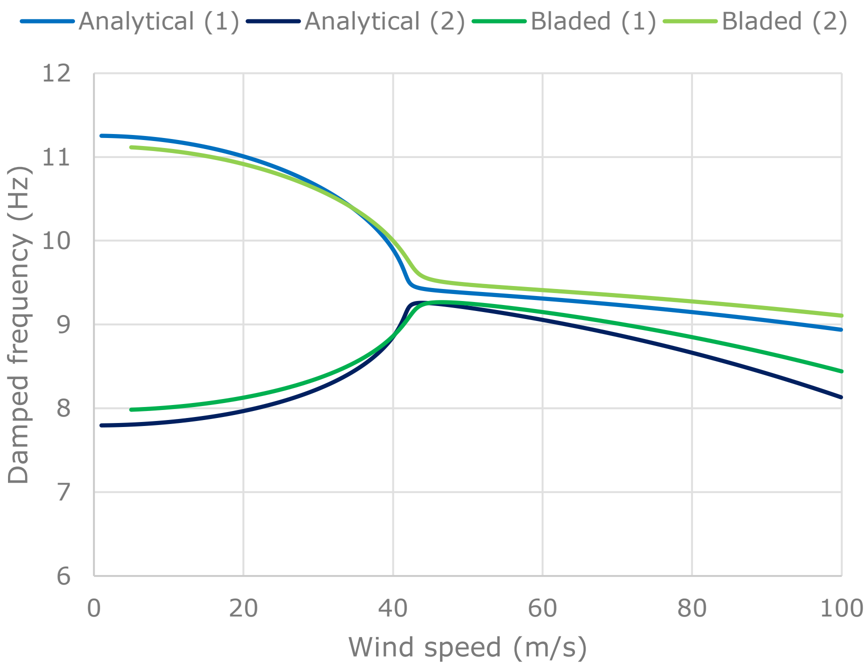
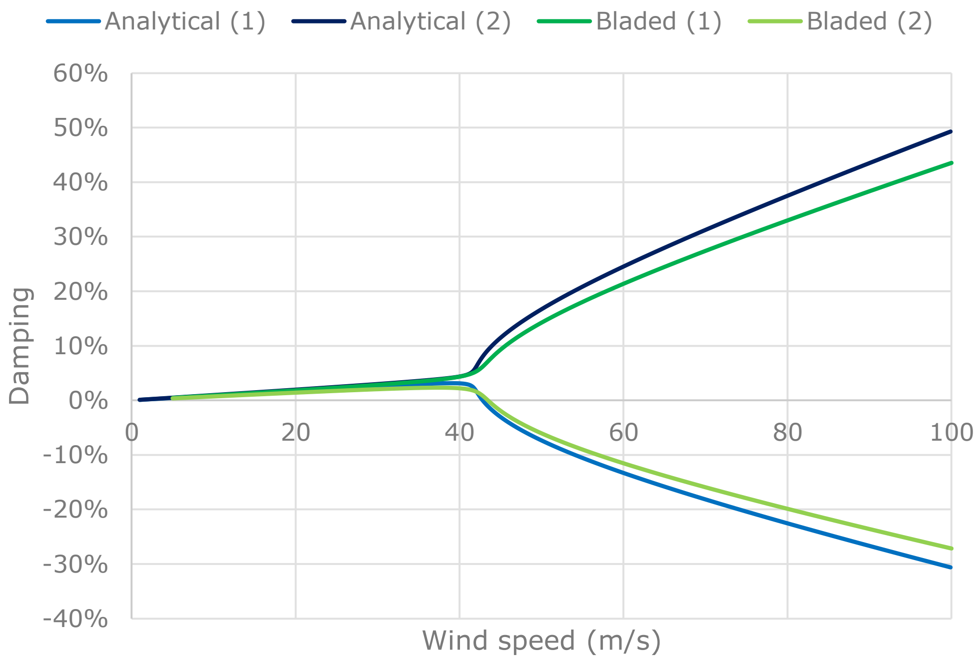
Validation against analytical 2D aerofoil

$$\begin{bmatrix} m & -md \\ -md & J \end{bmatrix} \begin{pmatrix} \ddot{h} \\ \ddot{\vartheta} \end{pmatrix} + \begin{bmatrix} K_h & 2\,\pi q_\infty S \vartheta \\ 0 & K_\vartheta - 2\,\pi q_\infty S \vartheta e \end{bmatrix} \begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$



- e is distance to aerodynamic centre
- d is distance to centre of mass





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Your ideas to extend stability tool…

- Currently we have two regimes:
  - TSR tracking
  - Parked with yaw
- Do we need more regimes
  - Vary TSR at fixed wind speed
  - Vary two independent variables (e.g. TSR and wind speed)
- Automatic rough aerofoil modification
- Explore uncertainties in lift/drag curves

Any questions?

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