

Campbell Diagram and Blade Stability Analysis

Frequency domain analysis

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Campbell Diagram in 4.8

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Campbell Diagram changes with New Aerodynamics (4.8)

- Linear System:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

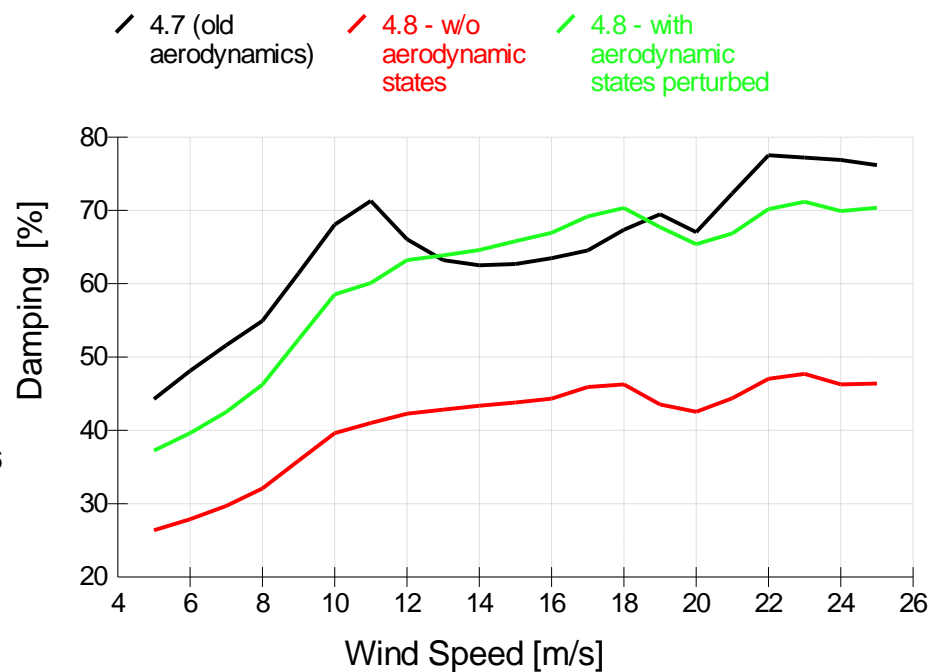
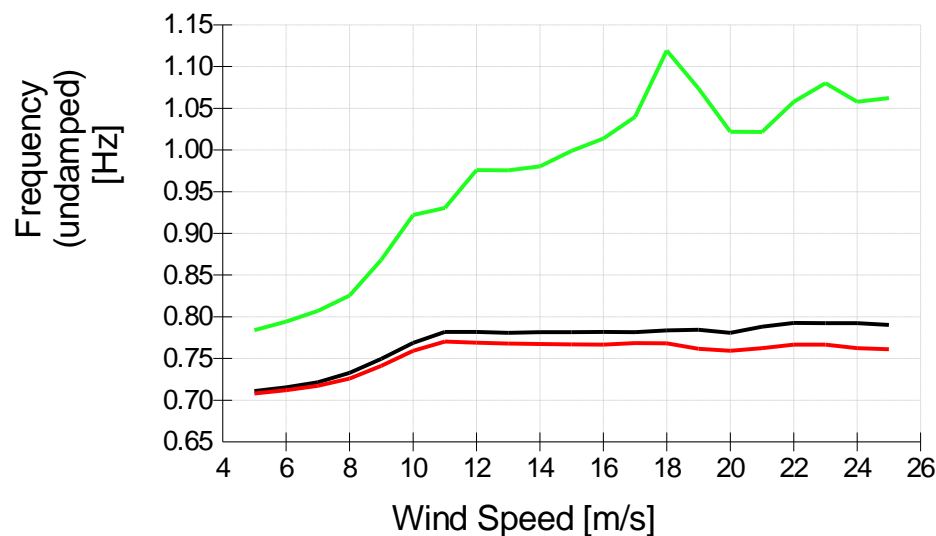
- In aeroelastic model, the state vector x is mostly two types:
 - Elastodynamic (structural modes etc...)
 - Aerodynamic (dynamic stall, wake etc...)
- In the time domain, these must be integrated.
- In the **frequency domain**, these must be **linearised**.
- Campbell diagram is an analysis of the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

$$\begin{pmatrix} \dot{q} \\ \ddot{q} \\ \dot{z} \end{pmatrix} = \begin{pmatrix} 0 & I & T_{qz} \\ M^{-1}\tilde{K} & M^{-1}\tilde{C} & T_{\dot{q}z} \\ T_{zq} & T_{z\dot{q}} & T_{zz} \end{pmatrix} \begin{pmatrix} q \\ \dot{q} \\ z \end{pmatrix} + Bu$$

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

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



At 16m/s:

Selected Point

Suggested name:

Rotor 1st flapwise mode B

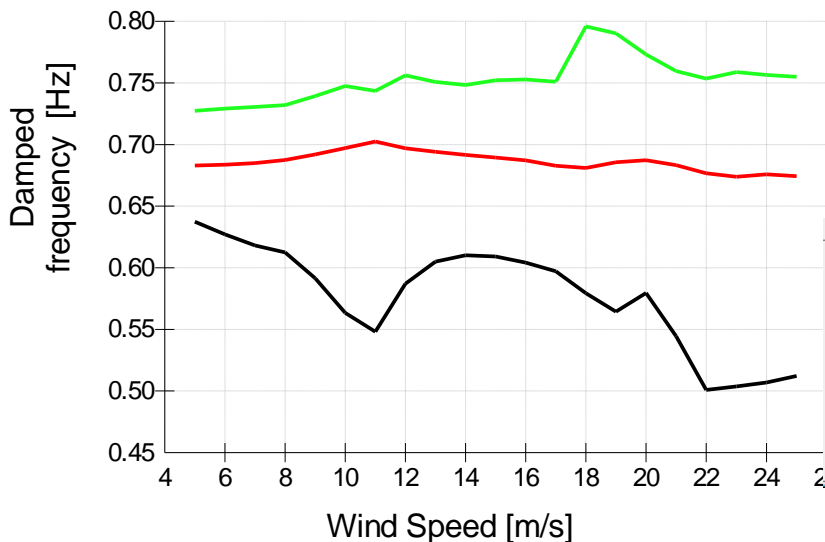
Main parameters:

rotor speed: 11.5241

frequency: 0.91918

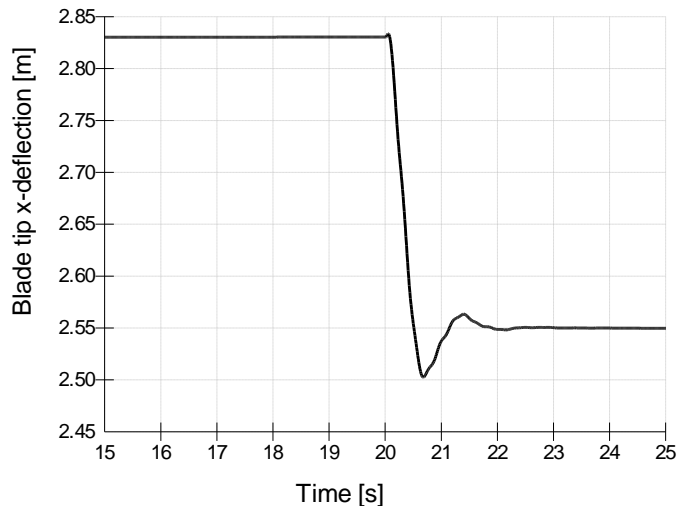
damping: 0.56586

Uncoupled mode contributions (name; contribution; phase)	View
Blade 1 1st flapwise mode	18.23% 55.5°
Dynamic stall Blade 1 at 52.2m attached flow 2	11.12% -27.5°
Dynamic stall Blade 1 at 50.2m attached flow 2	10.88% -28.5°
Dynamic stall Blade 1 at 48.2m attached flow 2	9.15% -29.7°
Dynamic stall Blade 1 at 46.2m attached flow 2	6.48% -31.0°
Dynamic stall Blade 1 at 54.2m attached flow 2	4.41% -26.6°
Dynamic stall Blade 1 at 55.2m attached flow 2	2.86% -26.0°
Dynamic stall Blade 1 at 56.2m attached flow 2	2.63% -25.3°



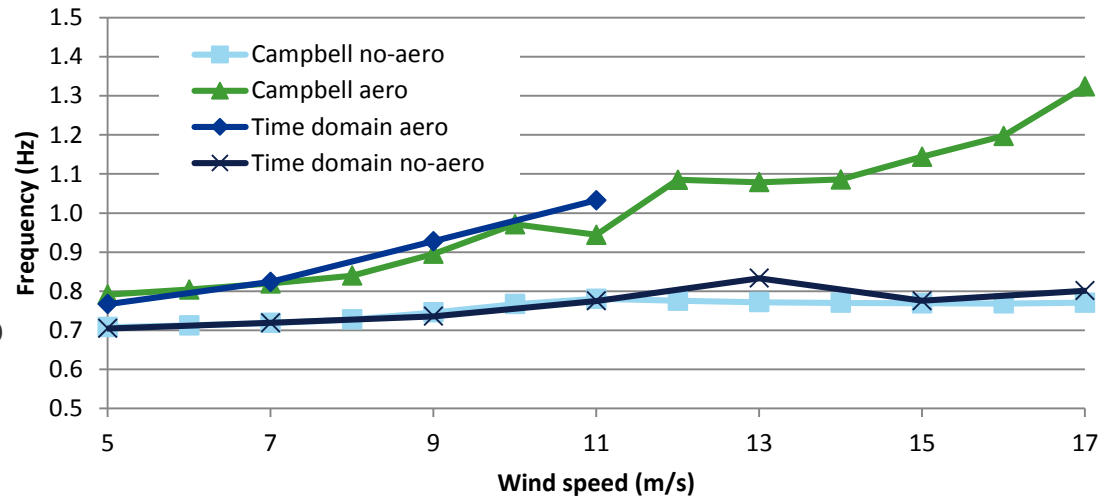
Comparison with time domain step response

- 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.

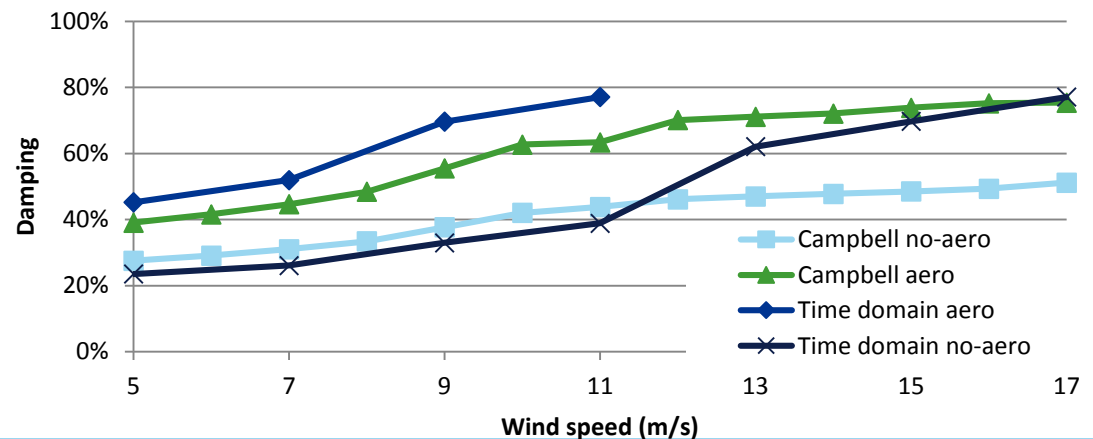


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1st flapwise frequency

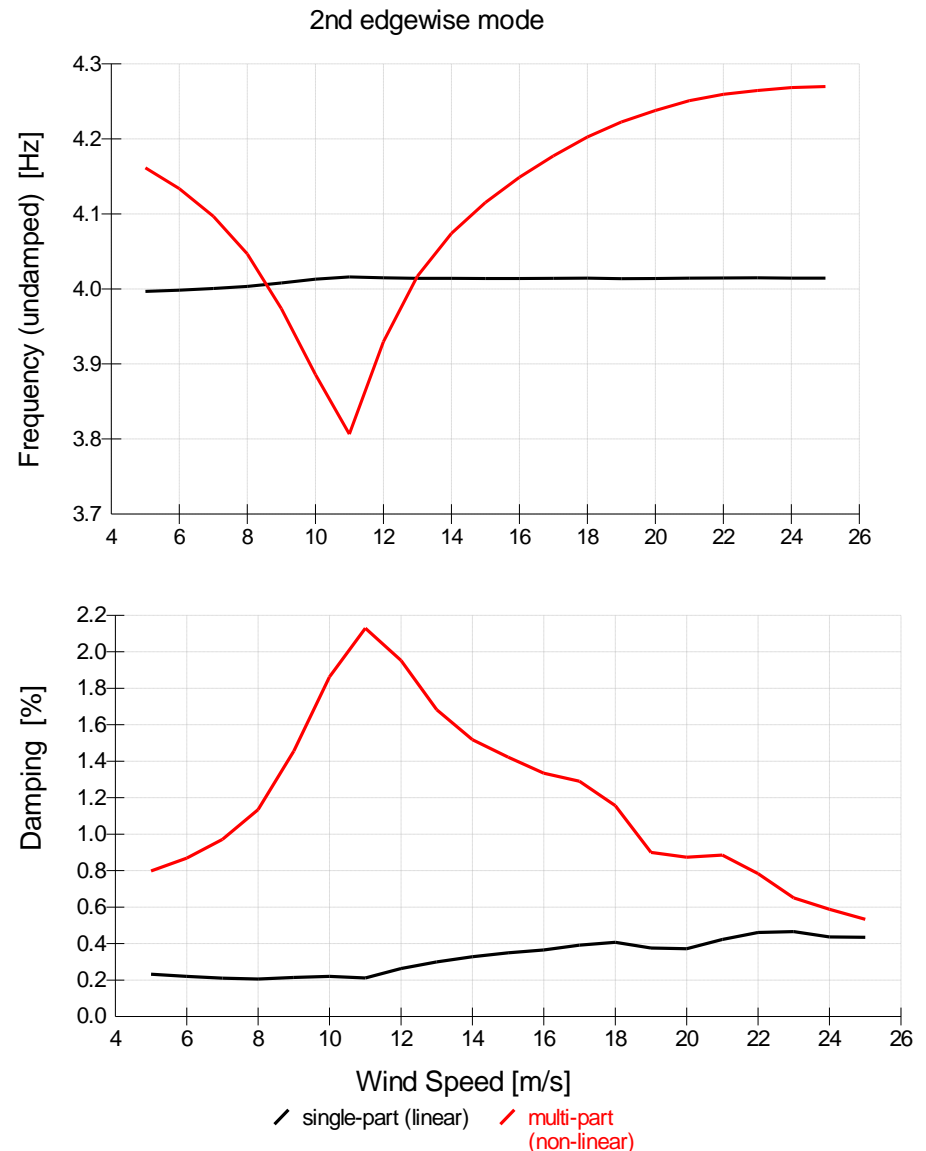


1st flapwise damping



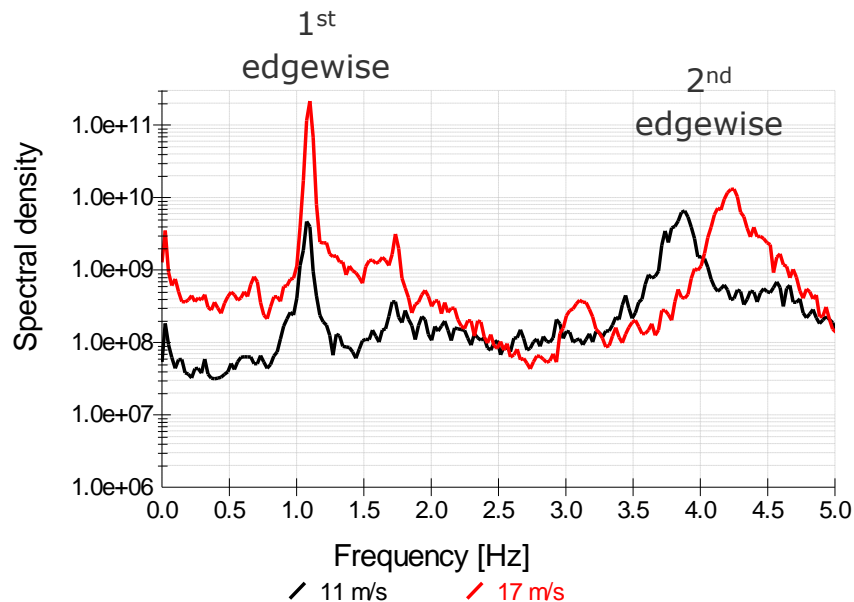
Edgewise modes – multi-part blade

- 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.

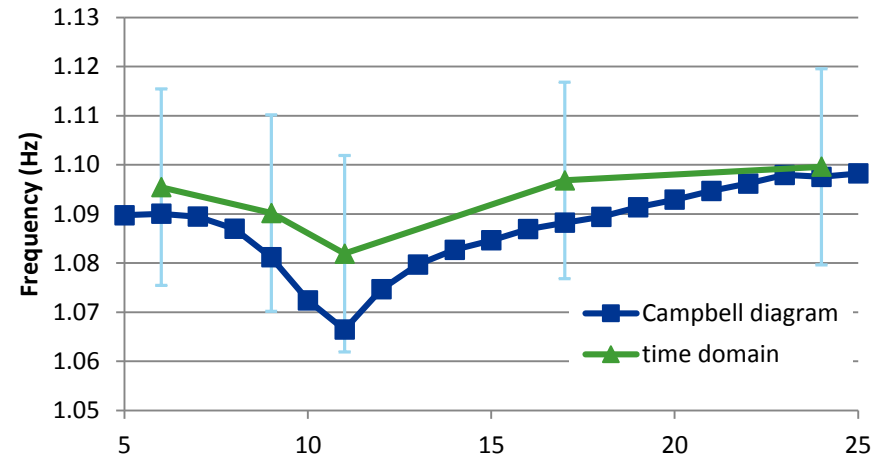


Edgewise modes – time domain verification

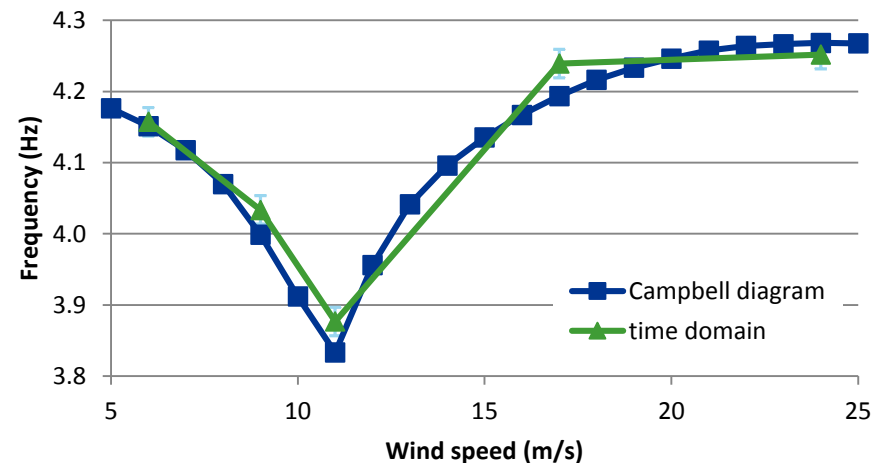
- Performed steady-state runs with high-pass filtered turbulent wind at each wind speed.
- In spectral analysis of blade root Mx or Fy load, frequency of edgewise peaks are easily identified.



1st edgewise frequency

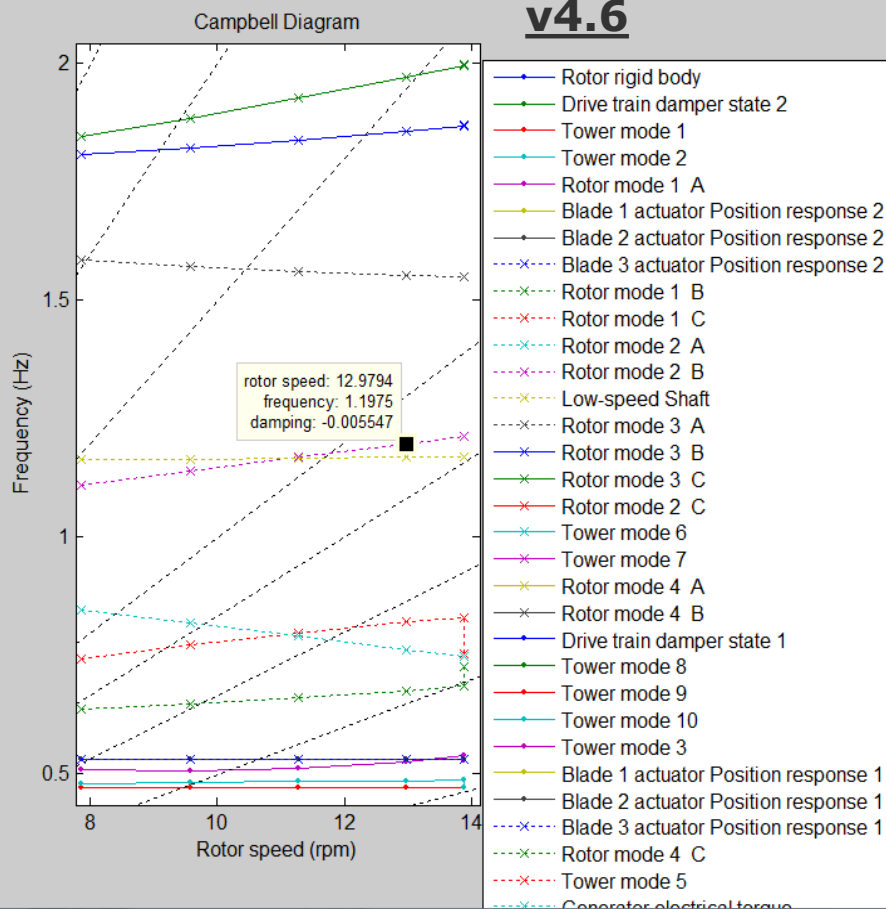


2nd edgewise frequency

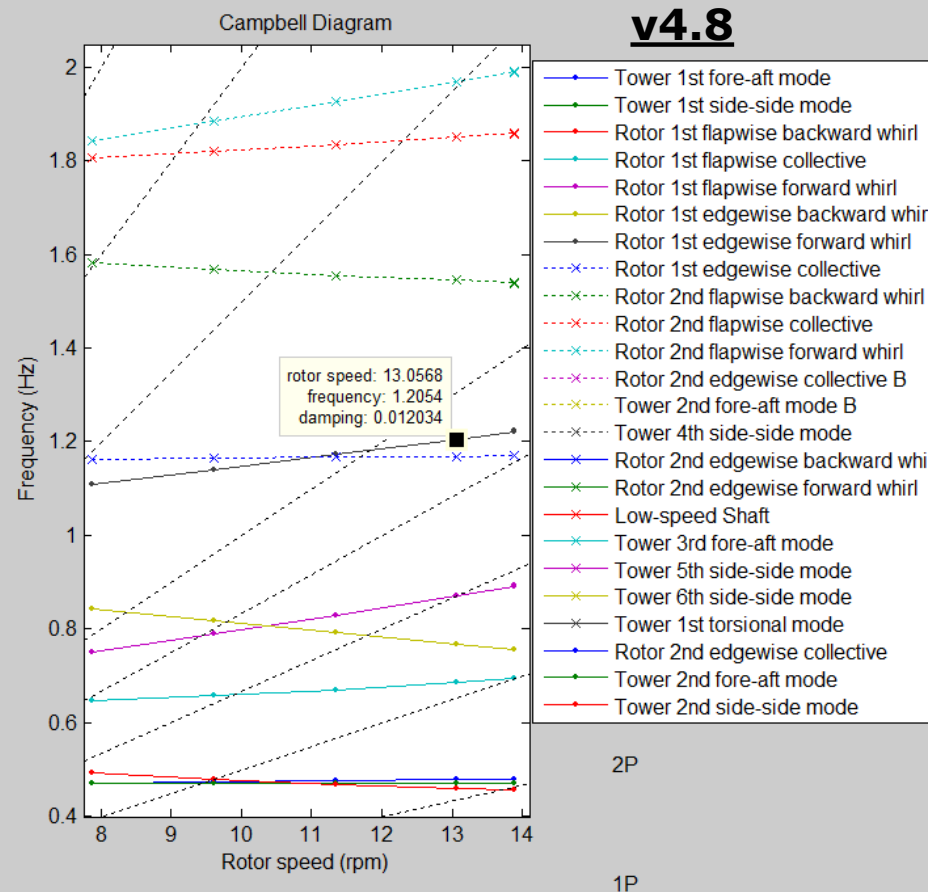


Campbell Diagram Naming Improvements

v4.6



v4.8



Selected Point

Suggested name:

Rotor mode 2 B

Main parameters:

rotor speed: 12.9794

frequency: 1.1975

damping: -0.005547

Other significant contributions:

Blade 2 mode 2 : 33.23 %

Blade 1 mode 2 : 33.17 %

Blade 3 mode 2 : 33.06 %

View

Selected Point

Suggested name:

Rotor 1st edgewise forward whirl

Main parameters:

rotor speed: 13.0568

frequency: 1.2054

damping: 0.012034

Other significant contributions:

Rotor 1st edgewise cosine cyclic 47.36% -53.1°

Rotor 1st edgewise sine cyclic 44.90% -143.1°

Tower 1st side-side mode 0.81% 122.2°

Rotor 1st flapwise sine cyclic 0.47% -19.6°

Rotor 1st flapwise cosine cyclic 0.45% 71.9°

Tower 3rd side-side mode 0.45% -156.6°

Tower 1st fore-aft mode 0.21% -38.1°

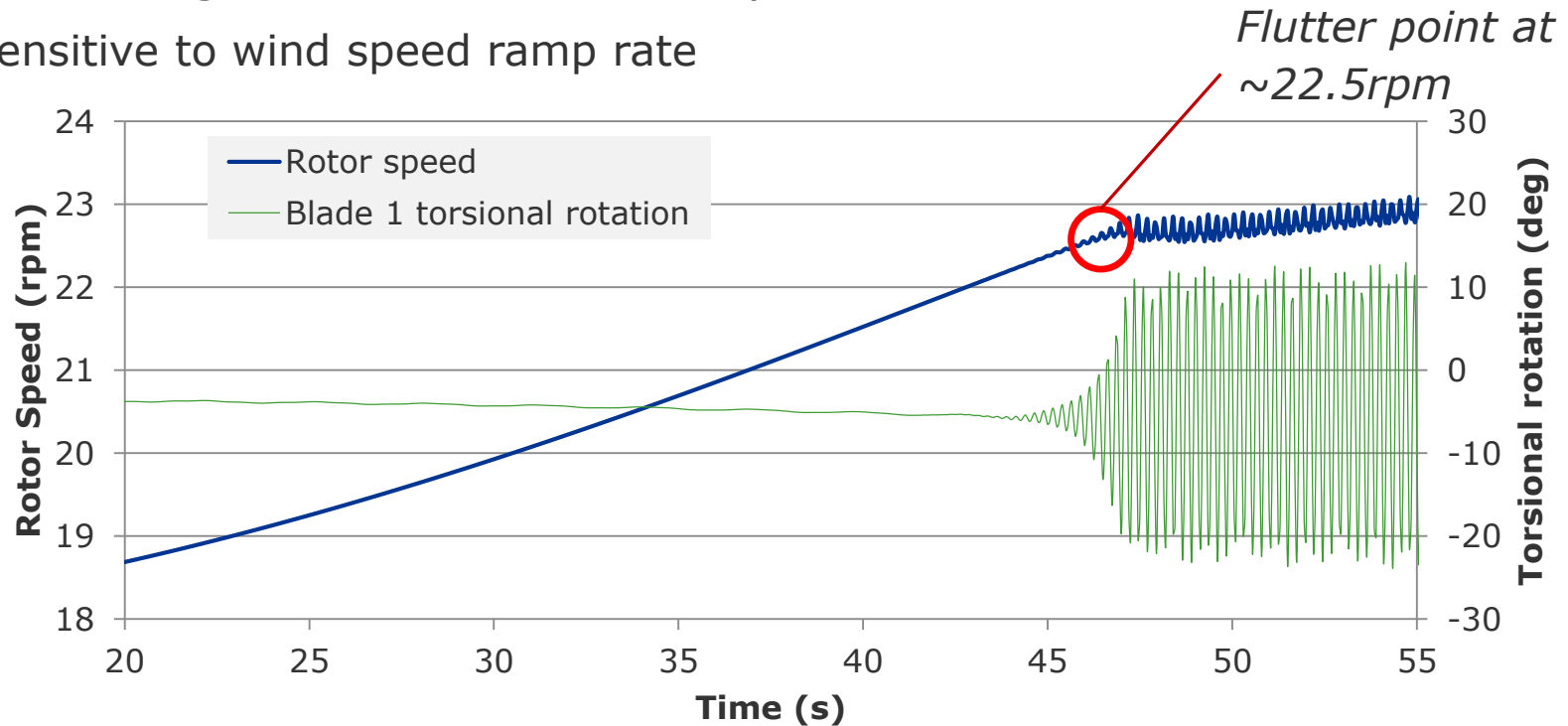


Blade Stability Analysis

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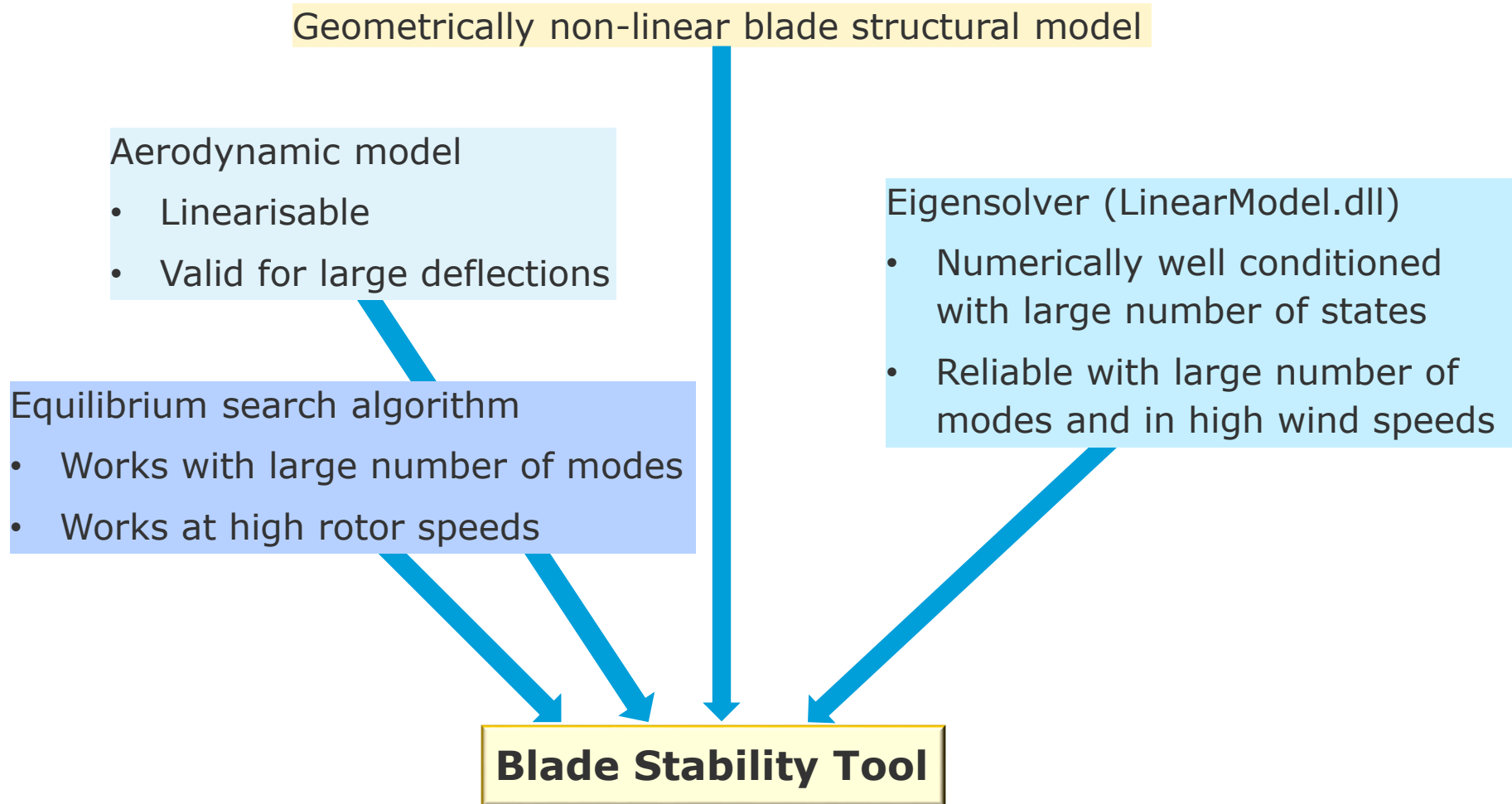
Time domain flutter analysis (all Bladed versions)

- 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



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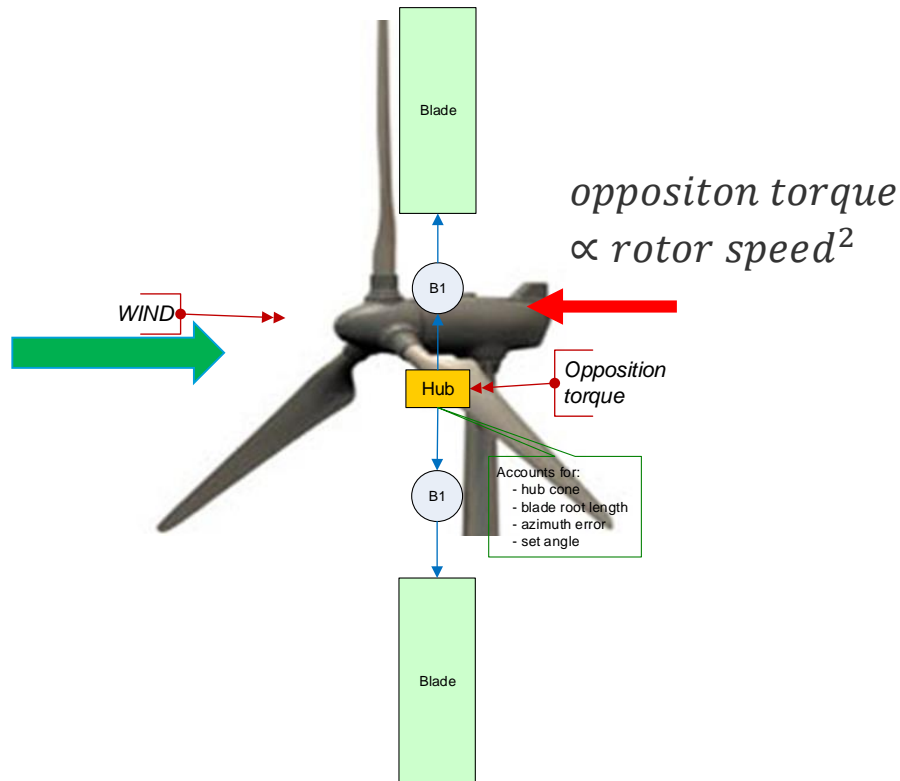
Pre-requisites of Blade stability tool



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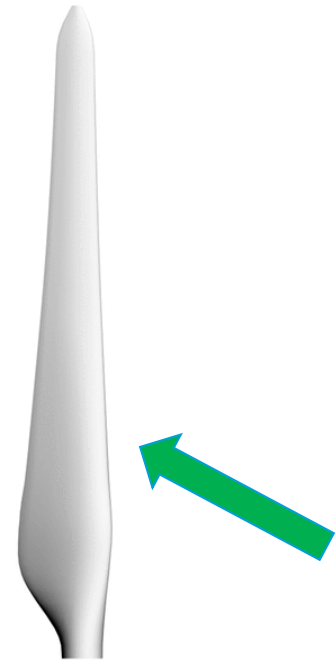
Types of Analysis

Tip-speed ratio tracking



Rotor speed increases linearly as wind speed is increased

Parked



Loop over wind speeds.
Can use different yaw angles

Blade Stability setup and results

Steady Parked Loads	
Model Linearisation	
Electrical performance	

Frequency domain analysis

Linearisation type: Blade stability analysis

Azimuth angle: 0 deg

Maximum frequency for plot: 20 Hz

Mode of operation: Free spin / tip-speed ratio tracking

Wind speed range: Min: 1 Max: 50 m/s

Wind speed step: 0.1 m/s

Torque speed gain: 0 Nm/(rad/s)²

Transform rotor modes to non-rotating frame: ☐

Analyse aerodynamic states: Dynamic stall only

Show advanced fields: ☐

Torque speed gain
Ratio of opposition torque to square of rotor speed. A value of zero gives a free-spin scenario. A non-zero value applies an opposition torque proportional to the square of rotor speed, which balances the aerodynamic torque.

OK Cancel

Run Name: Refresh Path:

bstab_10deg

Data Group:

Campbell diagram
Coupled modes
Rotor speed multiples
Unstable mode dampings
Blade 1 Aerodynamic information

Drive:

Prepare T-MON file
Prepare ASCII file

Unstable mode dampings

Variables:
Blade 1 1st torsional mode

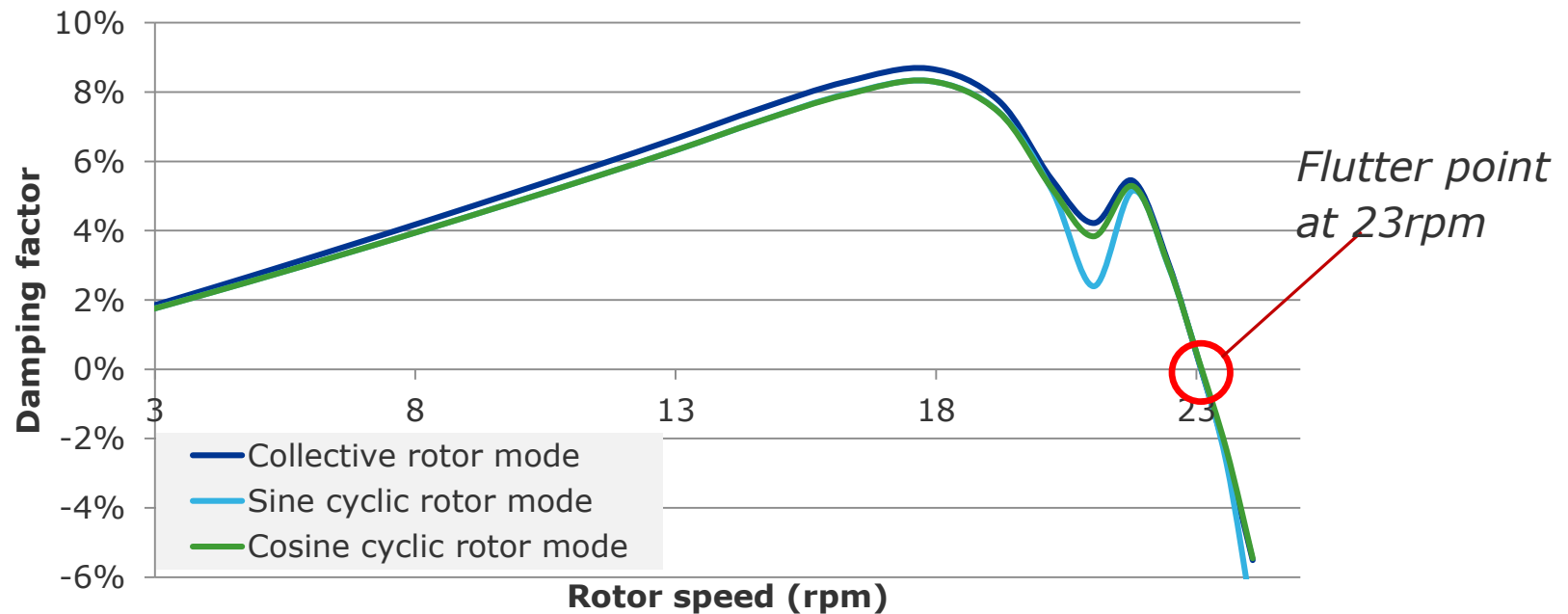
Independent Variables: (double-click to) Select value:

Independent Variables	Select value
Wind Speed X-Axis	

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Blade Stability Analysis – TSR tracking

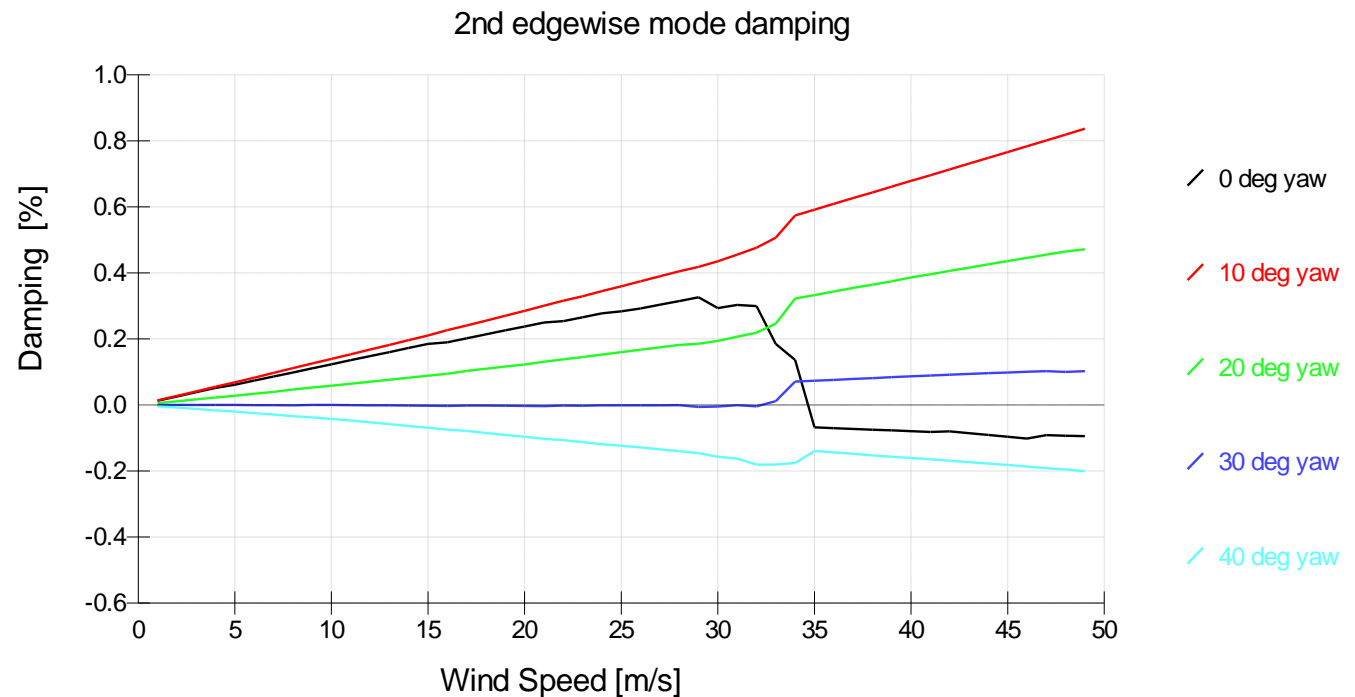
- Steady-state rotor speed and blade deflections determined at each wind speed.
- Model is linearised by perturbing all structural states (blade modes)
- Frequency, damping and mode shape calculated for all coupled modes.
- Provides **insight** into cause of instability (e.g. which modes are involved)



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Blade stability – Parked analysis

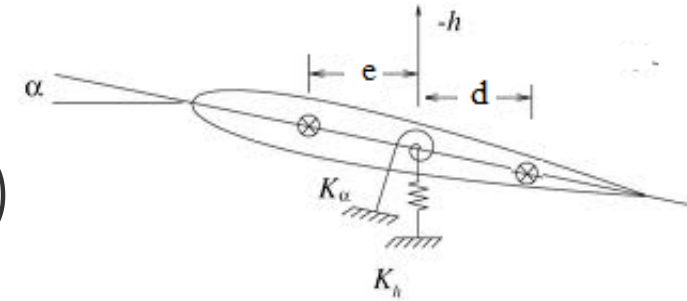
- Damping of all coupled modes at different wind speeds & yaw angles
- Highly sensitive to aerofoil and other data
- Up to what angles of attack are dynamic stall models valid?
 - Results at high angles of attack should be treated with scepticism



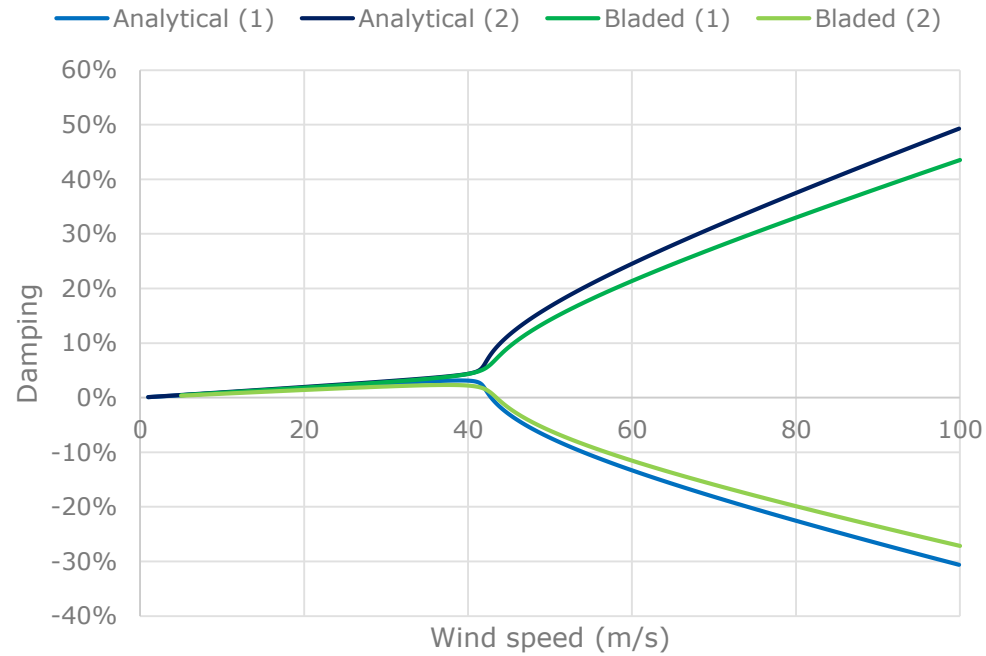
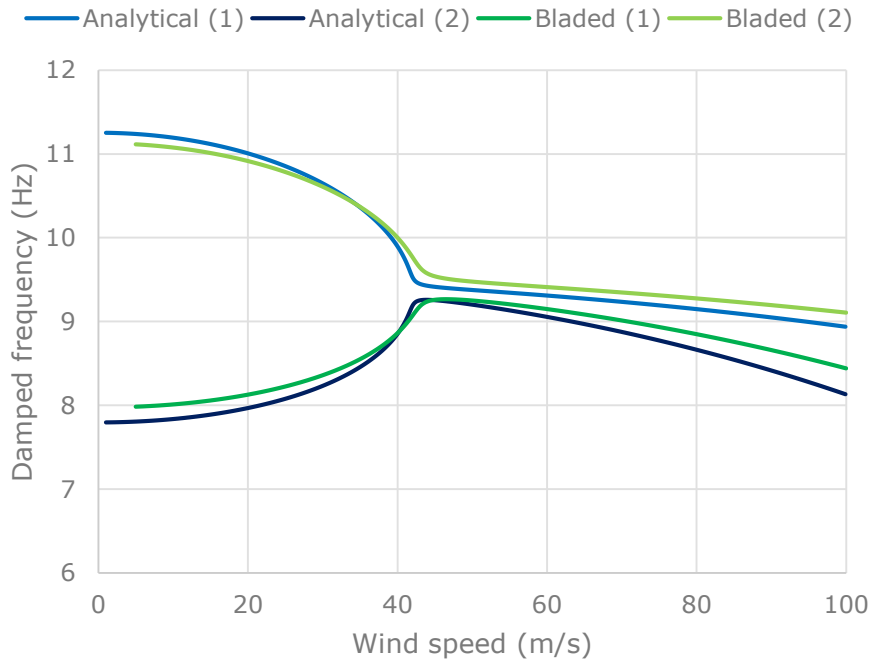
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Validation against analytical 2D aerofoil

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



- 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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SAFER, SMARTER, GREENER

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