

User Guide and Verification of Linearisation module in Bladed 4.8

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1 INTRODUCTION

Bladed 4.8 introduces a new aerodynamics implementation where for the first time the many aerodynamic states are handled together with the structural states and all other states. They are integrated together, and the aerodynamic states are now available for linearisation. This enabled the development of the Bladed Stability Tool which using linear analysis to assess the onset of flutter and other aero-elastic instabilities. This document covers some the verification work that has been done on the new linearisation code, and gives some guidance on how to use it.

1.1 Aerodynamic states

The method used by Bladed to linearise the model, calculate the coupled modes and their associated frequency and damping values is given in given in the Bladed Theory Manual, Chapter 11. A state space approach is taken, so the new aerodynamic models appear as new states in the linear models.

Aerodynamic states are of 1st order and typically represent a time lag. This can for example be the time lag for dynamic wake or the time lag for flow separation in the dynamic stall model. In Bladed 4.6 these states were “loosely” coupled to the model as they were integrated separately with a first order “dynamic wake time step”. In Bladed 4.8 the “dynamic wake time step” is no longer a user input as all unsteady aerodynamic effects are integrated with the central integrator. This new methodology brings more accurate integration on unsteady aerodynamics but also allows including unsteady aerodynamic effects in the linearisation. Table 1-1 provides an overview of the aerodynamic states that are used for different aerodynamic sub-models.

	Dynamic model	# states (per station)
Dynamic Stall	Øye stall	1
	Incompressible Beddoes-Leishman	5
	Pre-4.8 Beddoes-Leishman	8
	Compressible Beddoes-Leishman	11
Dynamic Wake	Øye wake	4
	Pitt-Peters wake	1
	Skew wake	1 (for rotor)

Table 1-1 overview of transfer function states

1.2 Coupled mode naming

1.2.1 Support structure modes

For support structure modes, the coupled mode is named after the uncoupled mode that gives the highest contribution. In case multiple coupled support structure modes share the same uncoupled mode as its prime contributor, then the coupled mode name is made unique by appending letters A,B,C, etc.

1.2.2 Rotor modes rotating frame

If no Multi Blade Coordinate (MBC) transformation is used for the rotor modes, then the following logic applies to naming the coupled rotor modes:

- If a single blade mode gives >75% contribution to the coupled rotor mode, then the coupled rotor mode is named after that blade mode. I.e. the mode is called "Blade" instead of "Rotor" mode
- Else, the rotor mode is named after its prime contributor and made unique by appending letters A,B,C, etc. in case multiple coupled rotor modes share the same uncoupled blade mode as prime contributor

1.2.3 Rotor modes non-rotating frame

If an MBC transform is applied then the individual blade modes are transformed to a set of rotor modes according to the equations stated in chapter 11 of the Bladed theory manual. For a three bladed rotor there typically is a collective, cosine-cyclic and sine-cyclic rotor mode. i.e. for the 1st flapwise modes of all blades will be renamed to rotor 1st flapwise collective, rotor 1st flapwise sine-cyclic and rotor 1st flapwise cosine cyclic. In case the number of blades is even there will be a differential mode as well.

After the transformation and renaming of the individual blade modes the coupled rotor modes are named. The whirling modes are identified following the logic in the table below

Coupled mode name	1st uncoupled mode	2nd uncoupled mode	Phase angle ($\Phi_2 - \Phi_1$)
Forward whirl	Sine cyclic	Cosine cyclic	> 0.0
	Cosine cyclic	Sine cyclic	< 0.0
Backward whirl	Sine cyclic	Cosine cyclic	< 0.0
	Cosine cyclic	Sine cyclic	> 0.0

If a coupled mode does not meet the criteria of the whirling modes, then the mode is named after its prime contributor. This is analogous with the naming logic of rotor modes in the rotating frame and support structure modes

2 CODE COMPARISON OF LINEARISATION MODEL

This section presents results for frequency and damping of coupled wind turbine modes calculated using the Bladed *Campbell Diagram* calculation. The results are compared to outputs from similar codes presented as part of the AVATAR project [1].

2.1 Linearisation benchmark using AVATAR rotor geometry

As part of Work Package 4 of the AVATAR project, a comparison in frequency and damping is carried out for the AVATAR rotor. In reference [2] the results are presented, including results from Bladed 4.4 delivered by CENER. In this section the original results are extended to include results from linearisation in Bladed 4.8.

2.1.1 Description of codes

A comparison is made against the following codes; a more thorough description for each of the codes can be found in reference [2]:

- CENER Bladed 4.4, CENER has used Bladed 4.4 using the old aerodynamics module.
- DTU HAWCStab2, analytical linearisation of nonlinear finite beam element model, using unsteady BEM.
- ECN BLADEMODE, linearized dynamic equations for bending and torsion of a rotating beam, using unsteady BEM or vortex wake
- NTUA GAST, multi-body approach and finite element discretization of flexible bodies, unsteady BEM
- POLIMI Cp-Lambda, multi-body approach, full finite-element models with unsteady BEM.

In Bladed 4.8 the following settings have been applied:

- Multi-part blade with 5 blade parts with 8 modes per part and 6 tower modes.
- Structural damping of 0.5% on first 6 blade modes and on all tower modes
- Aerodynamic states included and perturbed
- Geometric stiffness of "Full model with orientation correction" for blade and "axial only" for the tower.

2.1.2 Modifications to original AVATAR results

Initially all partners delivered the modal frequencies in ascending order for each wind speed. This has caused incorrect comparison of modes as in some occasions flapwise modes were compared with edgewise modes. Furthermore, sometimes the order of the mode shapes would change as frequencies changed with wind speed. In the results presented in this report, corrections have been made to the original data to ensure comparison of the same mode shapes.

2.1.3 Results

Figure 2-1 and Figure 2-2 show the damping and frequency of the first two tower modes. In terms of frequency all codes agree well. The side-side damping shows a significant spread although all codes do predict a positive damping.

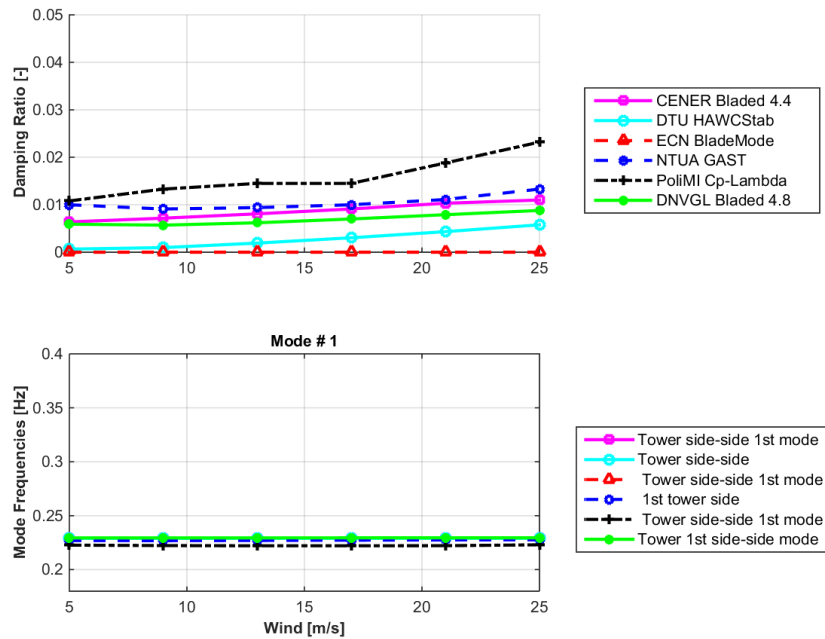


Figure 2-1 – Comparison for mode #1 (tower side-side)

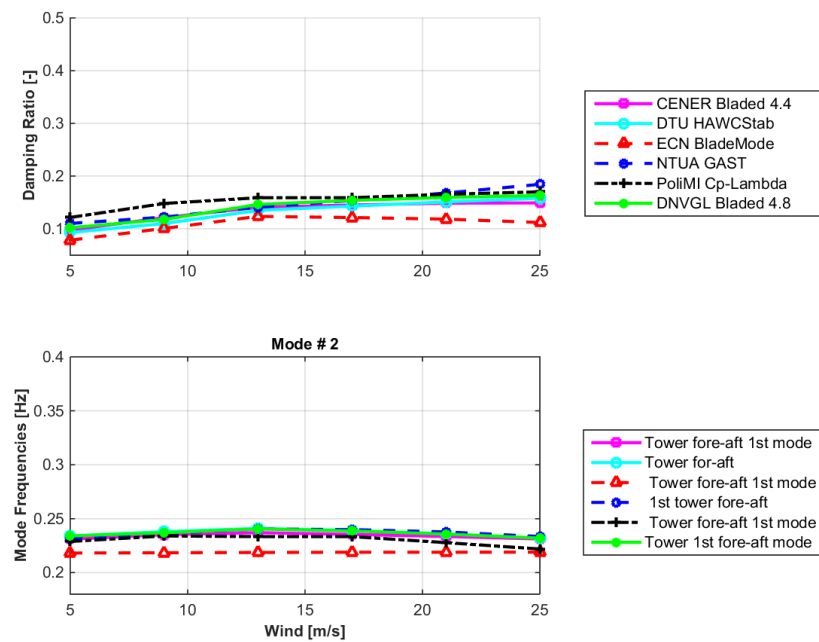


Figure 2-2 – Comparison for mode #2 (tower fore-aft)

Figure 2-3 shows a large spread in damping for the third eigenmode, which by all codes is defined as the rotor 1st flapwise backward whirling mode. Further, ECN and NTUA have not provided any results for these modes. POLIMI, DNV GL and CENER predict a frequency around 0.6 Hz. For the lowest wind speed the DTU results agree with the other codes, but the frequency increases to 1.2Hz.

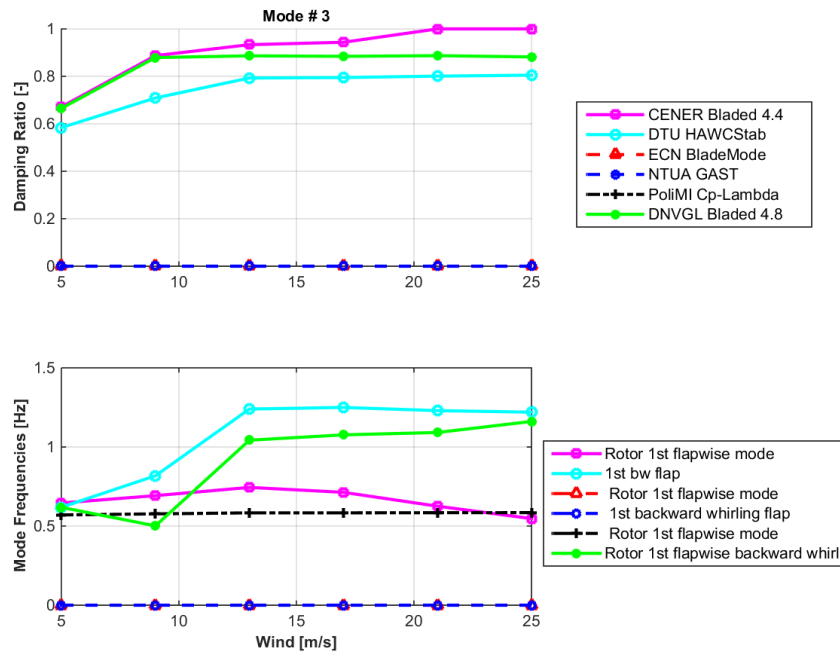


Figure 2-3 – Comparison for mode #3 (flapwise backward whirling)

Figure 2-4 shows the comparison in the collective first flapwise mode. With exception of the HAWCStab results, there is a reasonable agreement in frequency but again a significant spread in damping between the codes.

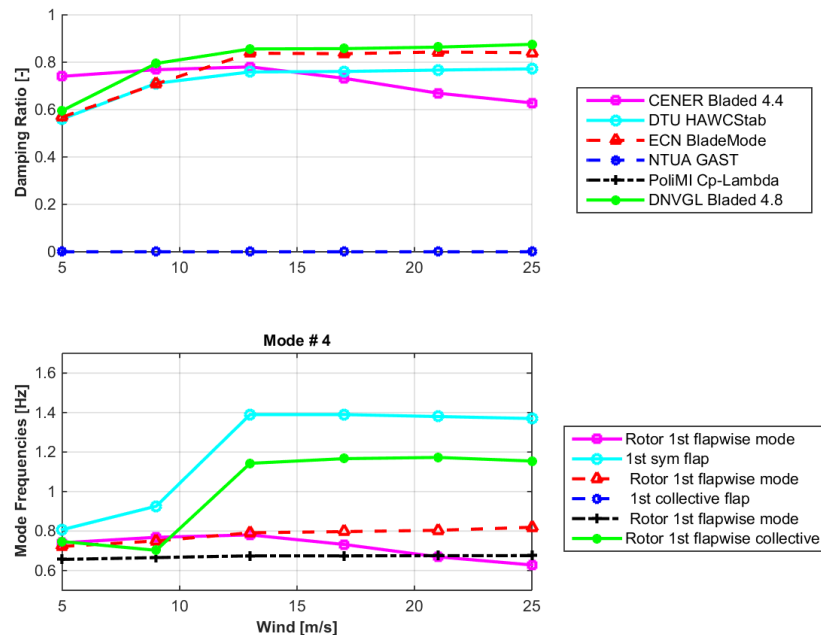


Figure 2-4 – Comparison for mode #4 (collective first flapwise)

Mode #5 is identified as a flapwise mode by all codes, as shown in Figure 2-6. Again, there is significant difference in damping and frequencies between the codes. DNV GL and POLIMI show good agreement in terms of frequency for all wind speeds.

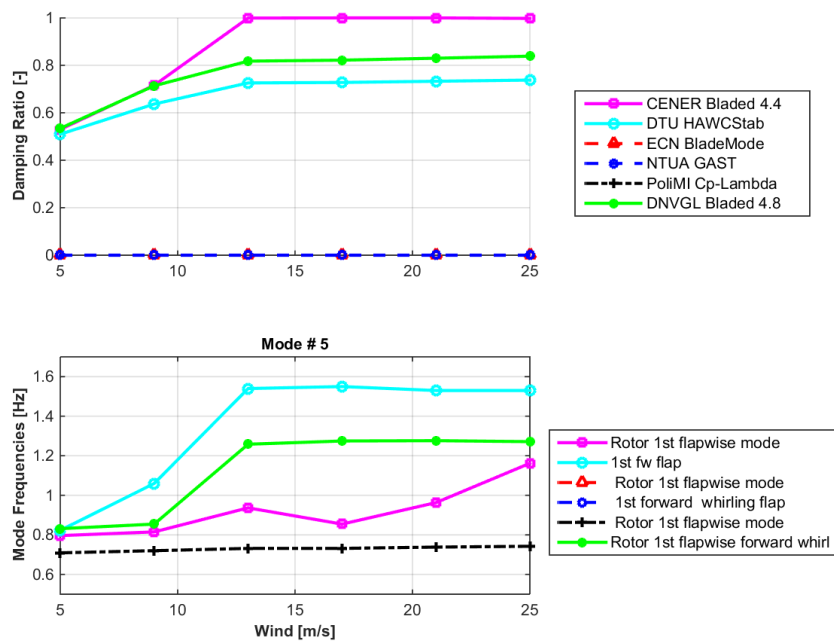


Figure 2-5 – Comparison for mode #5 (flapwise mode)

Mode #6 (Figure 2-6) is identified as an edgewise backward whirling mode. The codes generally have good agreement in frequency, only ECN BladeMode is deviating from the other codes. The damping curves all indicate positive damping and generally show a similar trend with wind speed.

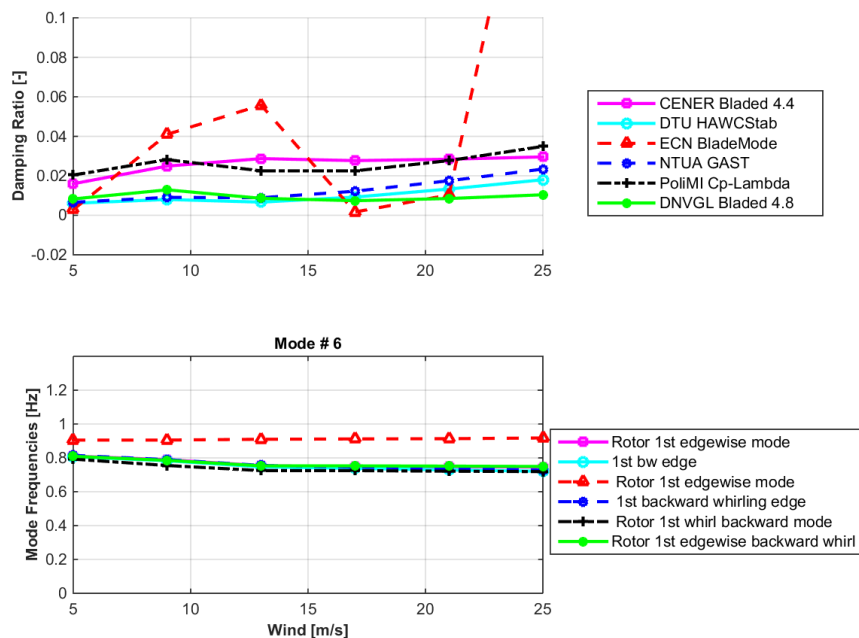


Figure 2-6 – Comparison for mode #6 (edgewise backward whirling)

For mode #7 a good agreement is found in terms of frequency in Figure 2-7. With the exception of Bladed 4.4 all codes show positive damping. The agreement in damping between NTUA, DNV GL and DTU is very good for this mode.

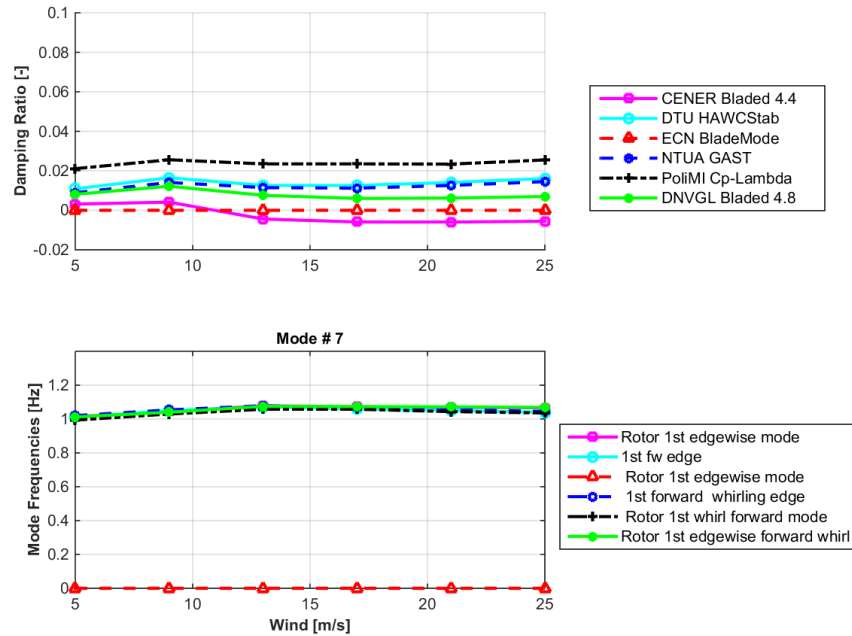


Figure 2-7 – Comparison for mode #7 (edgewise mode)

Mode #8 is identified as a tower 2nd fore-aft mode by CENER Bladed 4.4 and ECN BladeMode. The coupled mode from CENER shows significant contribution from the flapwise blade modes but is named after the tower mode as this mode gives the highest contribution. Although the frequencies are matching well, the mode is identified differently between partners.

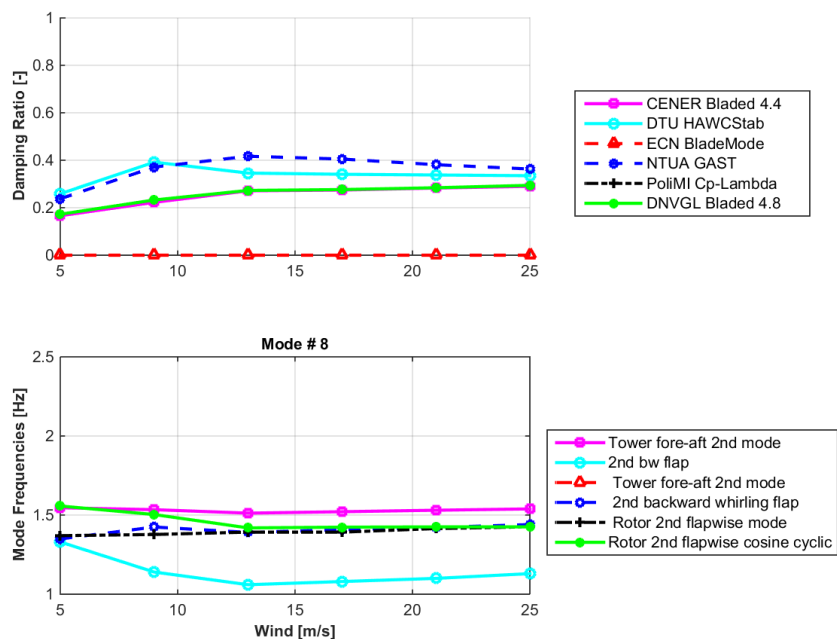


Figure 2-8 – Comparison for mode #8

For mode #9 (Figure 2-9) there is a good match in Frequency and damping between the codes. Although the mode name is identified differently between partners.

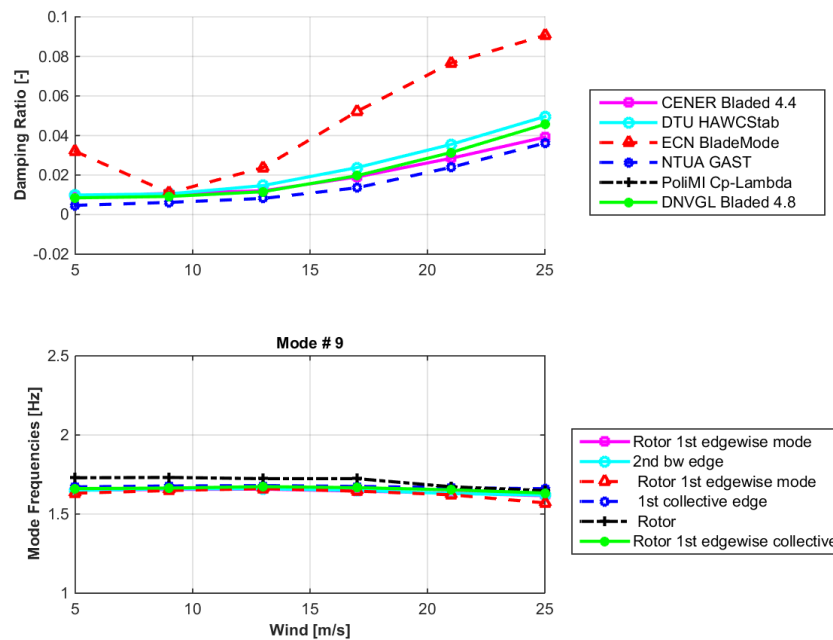


Figure 2-9 – Comparison for mode #9

2.1.4 Conclusions and recommendations

- There are significant differences in damping and frequency for most flapwise modes across the codes. These modes are generally highly damped and/or overdamped. The Bladed 4.8 results present the damped frequency, which for flapwise modes differs significantly from the undamped frequency.
- For the edgewise modes there is generally a good agreement in frequency and damping between the codes.
- Bladed 4.4 and 4.8 generally give similar predictions of frequency and damping. One notable point of difference is for mode #7 (edgewise mode). Bladed 4.4 predicts negative damping whereas Bladed 4.8 predicts positive damping. This may be due to increased flap-edge coupling captured by the non-linear blade model in Bladed 4.8.
- Significant relevant modelling changes between Bladed 4.4 and 4.8 include
 - o Bladed 4.4 uses a linear blade model, whereas Bladed 4.8 uses a non-linear blade deflection model.
 - o Bladed 4.8 uses a new aerodynamics implementation where the aerodynamic states are included in the linearisation.

3 VERIFICATION OF BLADE STABILITY TOOL

3.1 Comparison against analytical solutions for a 2DOF aerofoil

In this section the analytical flutter boundary for a 2 degree of freedom aerofoil will be compared against an equivalent numerical model in Bladed.

3.1.1 Governing equations

To test the basic functionality of the stability tool a comparison is carried out between an analytical solution of a two degree-of-freedom pitching and plunging aerofoil and the numerical solution in Bladed. Figure 3-1 shows an example of a 2D aerofoil that is attached to a linear (K_h) and a torsional (K_ϕ) spring. The aerofoil is assumed to have a mass (m) which is located at a distance (d) from the spring mounting position. Further the aerofoil has a rotational inertia (J).

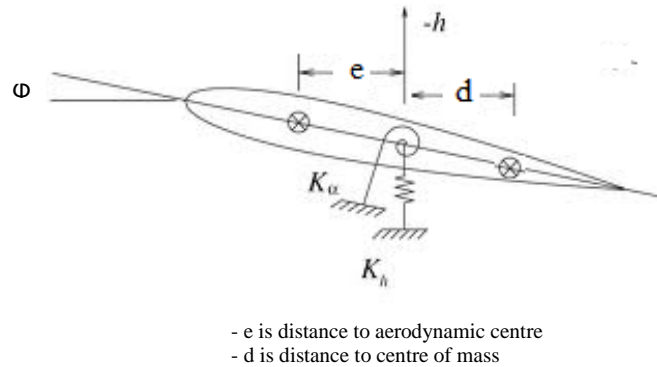


Figure 3-1 schematic of a 2DOF aerofoil

If one would assume flat-plate theory and fully steady aerodynamics, then the steady aerodynamic lift force and moment force can be described as:

$$\begin{aligned} L &= 2 \pi q_\infty S \vartheta \\ M &= 2 \pi q_\infty S \vartheta e \end{aligned} \tag{3-1}$$

Where:

- e, is the offset between the elastic and aerodynamic axis
- q, the dynamic pressure
- S, the wing surface area
- θ , spring rotation angle
- h, spring translational displacement

Then the equations of motion of the system are:

$$\begin{bmatrix} m & -md \\ -md & J \end{bmatrix} \begin{pmatrix} \ddot{h} \\ \ddot{\vartheta} \end{pmatrix} + \begin{bmatrix} K_h & -2 \pi q_\infty S \\ 0 & K_\vartheta - 2 \pi q_\infty S e \end{bmatrix} \begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{3-2}$$

Further if the damping due to the motion of the aerofoil is included the lift force can be rewritten as:

$$L = 2 \pi q_{\infty} S \left(\vartheta - \left(\frac{\dot{h} + \vartheta e}{V_{\infty}} \right) \right) \quad 3-3$$

Substituting this into the equations of motion yields:

$$\begin{bmatrix} m & -md \\ -md & J \end{bmatrix} \begin{pmatrix} \ddot{h} \\ \ddot{\vartheta} \end{pmatrix} + 2 \frac{\pi q_{\infty} S}{V_{\infty}} \begin{bmatrix} 1 & e \\ e & e^2 \end{bmatrix} \begin{pmatrix} \dot{h} \\ \dot{\vartheta} \end{pmatrix} + \begin{bmatrix} K_h & -2 \pi q_{\infty} S \\ 0 & K_{\vartheta} - 2 \pi q_{\infty} S e \end{bmatrix} \begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad 3-4$$

Assuming a harmonic solution of the form $h(t) = \hat{h} e^{\lambda t}$ then an eigenvalue problem is formulated yielding to the characteristic equation

$$A \lambda^4 + B \lambda^2 + C = 0 \quad 3-5$$

Where:

$$\begin{aligned} A &= mJ - m^2 d^2 \\ B &= K_h J + K_{\vartheta} - (md + me) 2 \pi q S \\ C &= K_h (K_{\vartheta} - 2 \pi q S e) \end{aligned} \quad 3-6$$

If the low frequency damping is included then the characteristic equations takes the form

$$A \lambda^4 + B \lambda^3 + C \lambda^2 + D \lambda + E = 0 \quad 3-7$$

$$\begin{aligned} A &= mJ - m^2 d^2 \\ B &= \frac{2 \pi q S}{U} (m e^2 + J) \\ C &= K_h J + K_{\vartheta} - (md + me) 2 \pi q S \\ D &= \frac{2 \pi q S}{U} (K_{\vartheta} + K_h e^2) \\ E &= K_h (K_{\vartheta} - 2 \pi q S e) \end{aligned} \quad 3-8$$

Equation 3-8 cannot be solved analytically and requires a numerical root finder. This is carried out using the `numpy.roots()` function in a Python script.

3.1.2 Comparison of Bladed to analytical solution for a flat-plate aerofoil

A Bladed model is created representing a two degree of freedom aerofoil. Modelling this simple case in Bladed is relatively challenging as Bladed is not designed to model two-degree of freedom systems. The 2D aerofoil is therefore modelled as a 100m blade with a uniform torsional and flapwise stiffness. The edgewise stiffness is kept a factor 5 above the flapwise stiffness to ensure that the first two blade modes are a flapwise and torsional mode. Further the mass and inertia is concentrated near the tip by using a split station at the last 1m of blade length. The first 99m of the blade is modelled with nearly zero mass and inertia. Finally, the first 99m of the blade uses an aerofoil with zeros as coefficients for lift, drag and moment coefficients. The last 1m of the blade is using a flat-plate aerofoil with $Cl = 2\pi \sin(\alpha)$.

To represent the bending/torsional stiffness of an equivalent single mass-spring system the following well-known cantilever deflection (δ) and torsional rotation (ϑ) formulas are used

$$\vartheta = \frac{FL^3}{3EI} \quad 3-9$$

$$\phi = \frac{ML}{GJ}$$

Where:

- M, bending moment applied at the free end of the beam
- L, beam length
- EI, beam bending stiffness
- F, discrete force applied at the free end of the beam
- GJ, torsional rigidity of the beam

The equivalent spring constants then are:

$$K_t = \frac{3EI}{L^3}$$

$$K_\phi = \frac{GJ}{L}$$

3-10

Table 3-1 summarizes all the inputs to the model.

Table 3-1 Parameters used for flutter calculation

Parameter	Quantity	Unit
Rotational inertia	0.75	Kgm
Mass	10	Kg
Linear spring constant	30000	Kg/m
Torsional spring constant	3000	Kg/m
Centre of mass	45	% chord
neutral axis	25	% chord
Shear centre	25	% chord
Flapwise frequency	7.9	Hz
Torsional frequency	11.1	Hz

The results in Figure 3-2 demonstrate a good match between the Bladed simulation and the analytical solution. In both cases the frequency branches merge around 43 m/s. At this same wind speed the damping of the torsional mode goes negative.

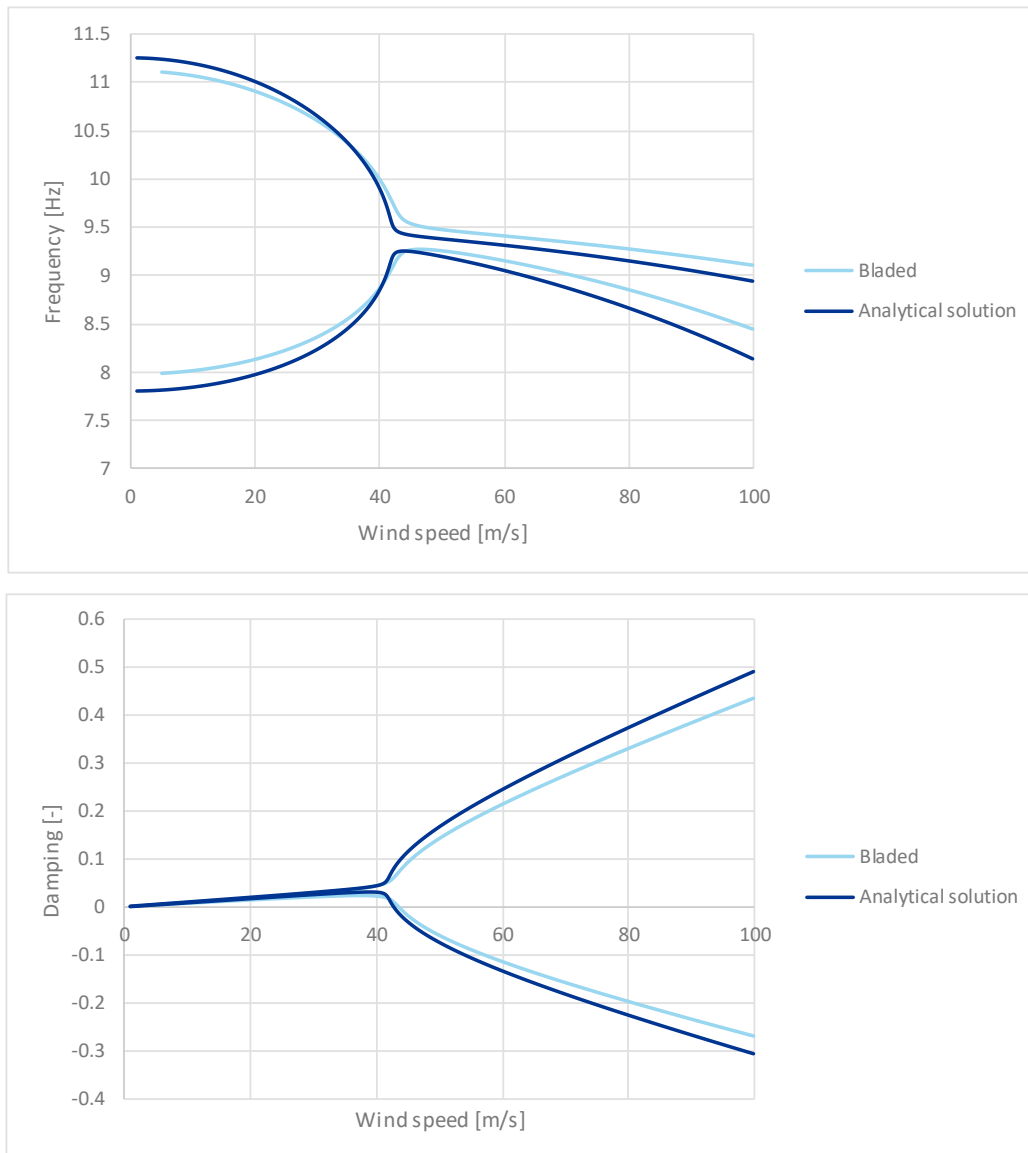


Figure 3-2 Analytical solution and numerical Bladed comparison of 2D aerofoil flutter problem

3.2 Flutter speed prediction of NREL 5MW rotor

This section presents the results of the flutter speed prediction of the NREL 5MW rotor. Contrary to stability analysis from a Campbell diagram, the rotor is assumed to be in a free spin without generator torque. Although this is a hypothetical situation, it does indicate the maximum rotor speed the rotor can achieve prior to going unstable.

Using the NREL 5MW rotor an assessment is made on the free spin flutter speed. The simulation is carried out both in time and frequency domain. For the frequency simulation, the wind speed is varied from 3m/s to 10 m/s. For each wind speed the free spin rotor speed and the frequency and damping of the coupled rotor modes is computed. The coupled modes are computed in the rotating frame of reference; i.e. no MBC transformation is applied.

Figure 3-3 and Figure 3-4 show the damping of the first torsional mode as a function of wind speed and rotor speed. The crossing with zero damping occurs around 7 m/s or 20.5rpm.

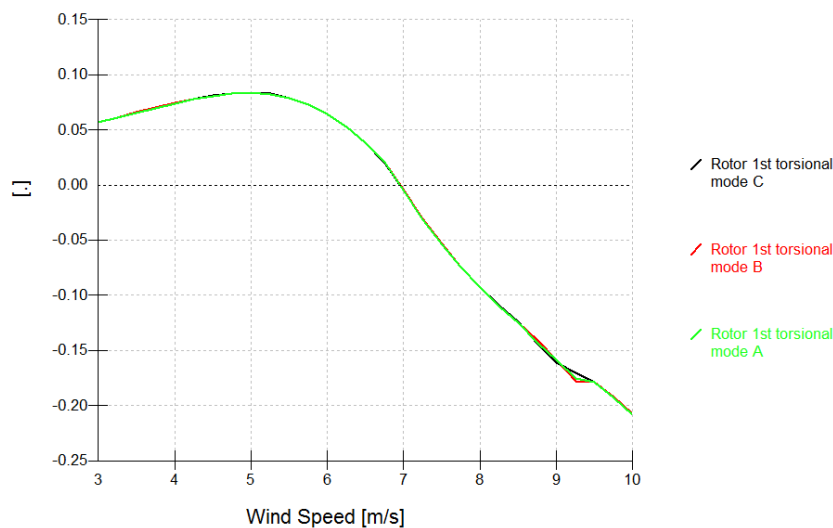


Figure 3-3 – Damping of 1st torsional mode as a function of wind speed, 10 blade modes

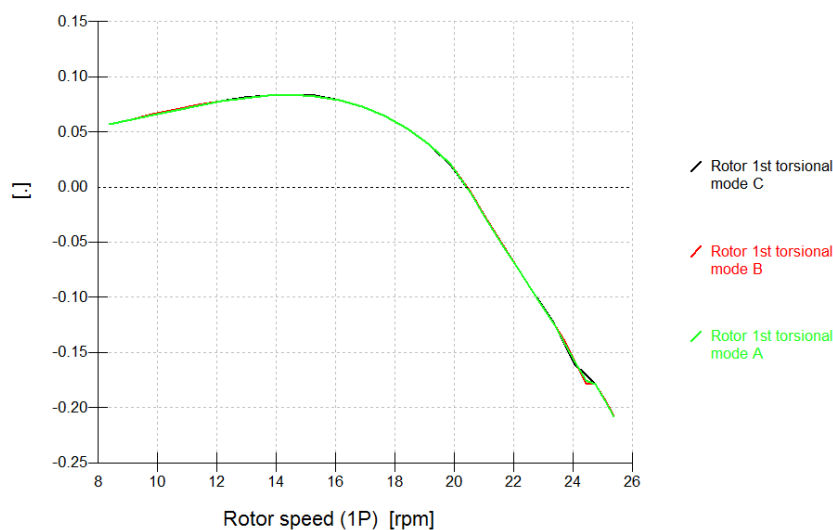


Figure 3-4 – Damping of 1st torsional mode as a function of rotor speed, 10 blade modes

For the time domain simulations, the wind was linearly ramped up with a rate of 0.02 m/s^2 with a starting value of 6 m/s . The generator inertia was set to zero in this simulation. The simulations show that the flutter point is reached at 19.8 rpm , which is slightly below the prediction of the frequency domain simulation of 20.5 rpm

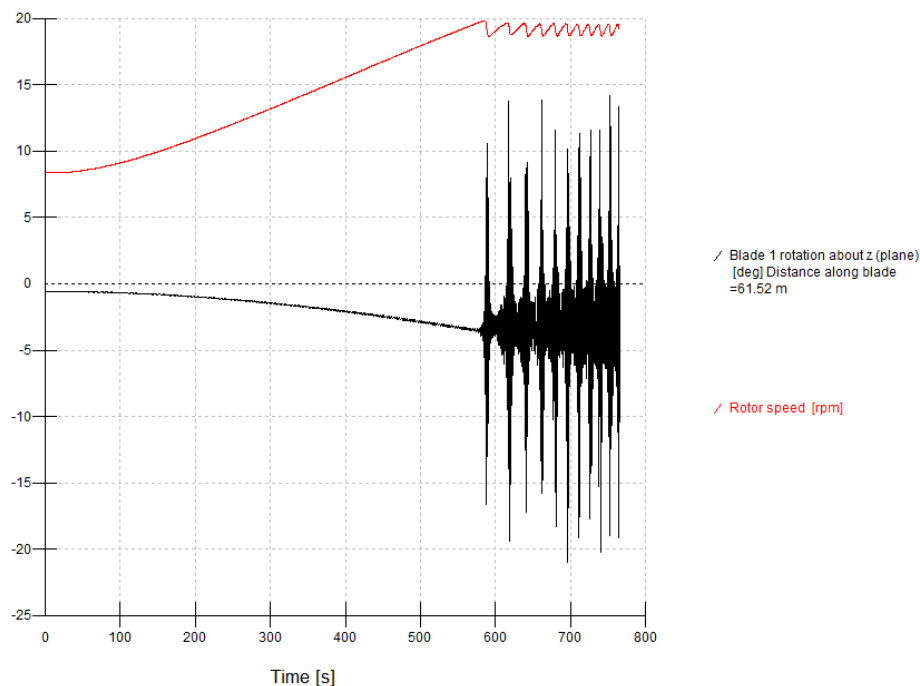


Figure 3-5 – Rotor speed as a function of time using a 0.02 m/s^2 wind speed ramp starting from 6 m/s

3.3 Effect of including aerodynamic states

3.3.1 Background

The linearisation model in Bladed 4.8 allows the user to choose whether to perturb and/or include the aerodynamic states. Aerodynamic states can be included in the model through the “Aerodynamics Control” screen by:

- Including a dynamic stall model. When enabled aerodynamic states related to unsteady aerofoil aerodynamics will be included in the model. See Theory Manual section 2.8 [3]
- Including a dynamic wake model. When enabled aerodynamic states related to the time delay of the dynamic wake are included in the model. See Theory Manual section 2.5 and 2.6 [3]

After including the aerodynamic states the user has the option in the “Model Linearisation” screen to perturb the dynamic stall or dynamic wake states or not. If the user selects to not perturb the aerodynamic states, then these states will not be linearised and will not be carried forward into the linear model. This option was added aiming at a compromise between computational speed and accuracy.

3.3.2 Numerical model

The work presented in this section is carried out using the numerical model of a commercial 3MW wind turbine with a rotor diameter of 125 m . The blade flexible model uses five blade parts eight modes per

part. A structural damping of 0.5% is assumed on the flapwise modes and 1% on the edgewise modes for the first five uncoupled blade modes. Six tower modes are included assuming a structural damping of 0.5%.

3.3.3 Effect on coupled modes in Campbell diagram

Table 3-2 and Table 3-3 present an overview of the change in frequency and damping of the first seven coupled system modes relative to the baseline model where aerodynamic states are included and perturbed. The following can be noted:

- Rotor flapwise modes are significantly affected in frequency and damping.
- The tower 1st fore aft mode shows a smaller difference. However, this mode is considered critical for control design and changes in damping and frequency will likely impact on the tower fatigue loads.
- The steady aero option generally matches well to the results of the other four models. The exception is the torsional mode frequency and damping.

Table 3-2 Comparison in modal frequency (%) using different linearisation settings. (difference (%) = $100 * (\omega_2 / \omega_1 - 1)$)

Mode name	Steady Aero	States included not perturbed	Perturb wake & stall	Perturb Wake	Perturb Stall
Tower 1st side-side mode	-0.01%	-0.10%	0.00%	-0.11%	0.00%
Tower 1st fore-aft mode	-0.19%	-3.47%	0.00%	-3.63%	0.13%
Rotor 1st flapwise mode B	-48.06%	-36.13%	0.00%	-37.19%	-1.48%
Rotor 1st edgewise mode B	0.03%	-0.12%	0.00%	-0.11%	-0.01%
Low speed Shaft B	0.00%	-0.07%	0.00%	-0.07%	0.00%
Rotor 2nd flapwise mode C	-2.08%	-0.18%	0.00%	-0.40%	0.28%
Rotor 2nd edgewise mode B	2.73%	-0.11%	0.00%	-0.11%	0.00%
Rotor 1st torsional mode A	-2.54%	0.47%	0.00%	0.95%	0.00%

Table 3-3 Comparison in modal damping (% of critical damping) using different linearisation settings (difference (%) = $\xi_2 - \xi_1$)

Mode name	Steady Aero	States included not perturbed	Perturb wake & stall	Perturb Wake	Perturb Stall
Tower 1st side-side mode	0.03%	-0.10%	0.00%	-0.09%	-0.01%
Tower 1st fore-aft mode	0.57%	-1.91%	0.00%	-1.81%	-0.27%
Rotor 1st flapwise mode B	13.68%	-26.32%	0.00%	-23.36%	-1.39%
Rotor 1st edgewise mode B	0.07%	0.05%	0.00%	0.04%	0.00%
Low speed Shaft B	0.02%	-0.03%	0.00%	-0.03%	0.00%
Rotor 2nd flapwise mode C	1.59%	-5.53%	0.00%	-5.60%	0.14%
Rotor 2nd edgewise mode B	-0.15%	-0.06%	0.00%	-0.06%	0.00%
Rotor 1st torsional mode A	-4.04%	0.86%	0.00%	0.50%	0.00%

To confirm the findings in above two tables a test case was run in time domain where the tower first fore-aft mode damping and frequency was measured. With a bespoke controller, the tower 1st mode was excited by applying a collective pitch oscillation at the tower natural frequency for a period of 10 seconds. Subsequently a system ID was carried out on the nacelle fore-aft signal from which frequency and

damping could be derived. This analysis confirmed that the full model where aerodynamic states are included and perturbed gave the best match to the time domain simulation.

3.3.4 Effect on blade stability prediction

Using the Bladed blade stability tool the predicted rotor speed at which rotor modes go unstable is computed. The rotor is put in a free spin at fine pitch and the wind is ramped up from 1 m/s to 6.5 m/s. Only rotor modes are modelled, no drive train or tower models are included. The results are summarised in Table 3-4. The following key results are obtained:

- For all cases the first rotor mode to go unstable is the 1st edgewise mode.
- The stability onset rotor speed is lowest for the full model where the aerodynamic states are included and perturbed.
- The Steady aero case predicts more modes that go unstable which don't go unstable using the other settings.

Table 3-4 Comparison in instability onset rotor speed as fraction of rated speed of different rotor modes using different aerodynamic settings


Rotor Mode to go unstable	Steady aero	States included not perturbed	Perturb all wake&stall	Perturb Wake	Perturb Stall
1 st edgewise	1.23	1.28	1.22	1.28	1.22
2 nd edgewise	1.43	n.a	1.59	n.a	1.59
4 th flapwise	1.70	n.a	1.86	n.a	1.87
3 rd edgewise	1.67	n.a	n.a	n.a	n.a
5 th flapwise	1.40	n.a	n.a	n.a	n.a
1 st torsional	1.42	n.a	n.a	n.a	n.a

Time domain analysis shows the rotor edgewise mode first going unstable at a rotor speed of 128% of rated rotor speed and a wind speed of 5.5m/s. This an exact match to the case where aero states are included but not perturbed. The two results may however not be exactly comparable as Table 3-4 provides the point of zero damping where the time domain will only show instability once the damping is negative.

3.3.5 Conclusions

The following can be concluded regarding the effect of aerodynamic settings on Campbell diagram and Blade stability analysis:

- For Campbell diagram, all models predict similar frequencies and damping. Exceptions are:
 - Flapwise frequency and damping is underpredicted when using steady aerodynamics. Adding dynamic stall and perturbing the states is necessary to get good results.
 - The tower fore-aft mode damping is well predicted when using steady aerodynamics, but not when including but not perturbing dynamic stall states.
 - Steady aero under predicts the damping of the torsional mode.
- For blade stability, all models predict that the edgewise rotor mode first goes unstable. The steady aerodynamics model matches the full model. Including but not perturbing the dynamic stall states leads to an increase in instability onset speed.
- For blade stability, the steady aero model predicts many more modes that go unstable compared to the models that do include aerodynamic states.
- For both blade stability and Campbell diagram, there is no benefit to include and perturb the dynamic wake states.



The following is recommended:

- States that are included in the model should also be perturbed. I.e. the option to include but not perturb aerodynamic states is not recommended
- For Campbell diagram, it is considered sufficient to use steady aerodynamics. For analysis of higher frequency rotor modes, it is however advised to include the aerodynamic states.
- For blade stability analysis, it is recommended to include and perturb all the dynamic stall model.

4 USER GUIDE LINEARISATION SETTINGS

4.1 New linearisation screen in Bladed 4.8

Similarly to Bladed 4.7 and older, the new linearisation screen offers the choice between carrying out a Model Linearisation calculation or a Campbell diagram. In addition, for users with the blade stability tool a 3rd option is present for blade stability analysis

4.1.1 Model linearisation

Most the settings for model linearisation in Bladed 4.8 have not been changed compared to Bladed 4.7 and older. New advanced options are available giving the user control over the perturbation size and aerodynamic settings. These settings are discussed separately in paragraph 4.1.4.

4.1.2 Campbell diagram

For the Campbell diagram calculation, the inputs have remained mostly the same. The following additional inputs are now available:

- **Maximum Frequency for plot:** This controls the maximum frequency of modes that are plotted in the Campbell diagram. In case a model contains high-frequency blade or support structure modes, this setting can be useful to improve the responsiveness of the Campbell diagram view.
- **Custom LinearModel.dll path:** LinearModel.dll performs linear analysis on model linearisation data produced by dtbladed.exe and creates the Campbell diagram. The user may choose a custom LinearModel.dll rather than the one in the installation directory.

4.1.3 Blade stability analysis

The blade stability analysis feature, released in Bladed 4.8, performs a frequency domain analysis of the turbine rotor in steady state. The analysis provides outputs of damping and frequency of all the coupled rotor or blade modes plotted against wind speed. It is a similar analysis to the Campbell diagram but the main differences are:

- Only the rotor is modelled
- Allows analysis over a wide range of inflow conditions rather than being constrained to normal operating conditions
- Improved initial condition finding suitable for extreme conditions.

For outputs, the blade stability analysis produces a Campbell diagram plot and frequency and damping curves of all coupled modes. It is primarily the damping curves that will be of most interest as this allows the user to detect possible instabilities by finding damping curves that have negative damping.

The coupled mode frequencies and damping are plotted against wind speed, but can also be plotted against rotor speed by using an output channel as the x-axis in the data viewer.

Bladed currently allows two types of blade stability analysis: tip-speed ratio tracking and parked, which are described in the sections below

Constant Tip-Speed Ratio

In this setup, the user chooses a range of wind speeds, in response to which the rotor will have a certain rotor speed. The pitch angle is usually at fine or at an operational pitch angle in these simulations.

At very high rotor speeds, it often becomes difficult to find initial conditions. If the analysis reaches this point, it will complete without analysing the last few points. This allows the user to set the upper wind speed with some freedom.

The user can specify a 'torque speed gain' which determines an opposition torque applied against the rotor aerodynamic torque (in a gearless case this is equivalent to a generator torque and otherwise equivalent to a generator torque applied on the high-speed side of the gearbox). The torque speed gain is defined as:

$$\text{Opposition torque} = \text{Torque speed gain} * (\text{rotor speed})^2$$

To follow the optimal mode tip-speed ratio, the torque speed gain can be set as:

$$\text{Torque speed gain} = \text{optimal mode gain} * (\text{gearbox ratio})^3$$

If the torque-speed gain is set at zero then the rotor will be in a free spin (i.e. zero generator torque).

Parked Analysis

The user can perform a parked analysis where the rotor speed is locked at zero rpm. Because the rotor freedom is disabled, only one blade is analysed as it is assumed that the blades do not couple.

Notes on inputs

- The user can freely set the **maximum wind speed** to a high value. When the turbine gets into very extreme operating conditions, at some point the turbine will fail to find adequate steady state conditions. At this point, Bladed will finish the blade stability analysis and proceed to complete the analysis with the wind speeds already analysed. The point of steady state failure typically happens at around twice the rated rotor speed.

4.1.4 Advanced options

The following options are new in Bladed 4.8 and not present in Bladed 4.7 or older.

- **Perturb aerodynamic states:** With 4.8 aerodynamics, there is the option to perturb all aerodynamic states in the linearisation. This means the A-matrix of the linear model will include all aerodynamics states in addition to the structural states. The user can further select to perturb only dynamic wake or dynamic stall states. Including the perturbation for the aerodynamic states will lead to a longer analysis time and a larger A-matrix. It is however recommended to always perturb aerodynamic states that are included in the model. (see section 3.3)
- **Maximum frequency to analyse:** A limit on the maximum frequency of the coupled blade modes that are perturbed in the analysis.
- **Number of perturbation points:** Number of values that each state gets perturbed to either side of the equilibrium point.
- **State relative perturbation:** The magnitude of the state perturbations relative to the absolute steady-state values.
- **Absolute tolerance perturbation scale:** States that have an equilibrium value of zero will be perturbed by this number times the absolute tolerance of that state.



4.2 Aerodynamic options for linearisation

The linearisation screen in Bladed 4.8 gives the user more options to configure the calculations. If the user wants to replicate linearisation results of Bladed 4.7 or lower, then the following aerodynamic options need to be selected in the Aerodynamics control screen:

- **Dynamic wake:** Frozen wake
- **Dynamic stall model:** No dynamic stall

With these settings, the setting on “Perturb aerodynamic states” in the linearisation screen becomes irrelevant as the model does not contain any aerodynamic states if dynamic wake and dynamic stall are turned off.



5 REFERENCES

1. <http://www.eera-avatar.eu/>
2. A. Croce, Comparison of models with respect to stability analysis, AVATAR, 15 October 2015
3. DNV GL - energy, Bladed Theory Manual, version 4.8, 2016