Blade modelling in Bladed 3.85 – 4.x

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Doc No: 110052-UKBR-T-23

Issue: B

Date of issue: 12 May 2016

Updates in issue B

- Updated note on geometric stiffness in Bladed 4.5
- Updated details of multi-part blade model in Bladed 4.7

SUMMARY

This document describes the improvements in Bladed most relevant to blade modelling that occurred between Bladed versions 3.85 and 4.7.

Section 1 summarises the changes to the blade model between Bladed 3.85 and 4.7. Section 2 describes each of the changes in more detail.

1 MODELLING CHANGE SUMMARY

The table below gives a summary of the strengths and limitations of the blade model in 3.85 and successive improvements in the later Bladed versions.

3.85	• Modal approach to dynamics ↑ • Centrifugal stiffening included ↑ • Rotor modes ↓ • No blade torsional DoF ↓ • Lumped blade pitch inertia ↓ • Limited blade output coordinates ↓
4.0	• Rigorous multibody dynamics • Individual blade modes • Coupled flap and edge modes • Torsional blade DoF • Non-constant pitching inertia • Shear axis offset from neutral axis • Blade loads output in principal axis coordinates
4.1	• Aerodynamic and User-defined output axes • Pitch bearing can be part way along the blade
4.2	• Pitch actuator DLL interface
4.3	• Bend-twist coupling • Campbell diagram Multi-blade coordinate transform • Improved Beddoes-Leishman dynamic stall
4.4	• Shear axis can have different orientation relative to neutral axis • New pitch actuator model and User Interface • Extra User Axes outputs (align to Aero axes)
4.5	• Apply point loads to blades • New torsional geometric stiffening model
4.7	• Multi-part blade (beta)

2 MODELLING CHANGE DETAILS BY VERSION

This section discusses the major changes and new features between versions from Bladed 3.85 to 4.5.

2.1 Bladed 3.85 vs Bladed 4.0

The release of Bladed 4.0 marked a significant step forwards for the structural dynamics model in Bladed. For this release, a Multibody dynamics model was developed, allowing rigorous modelling of the structural dynamics of the individual turbine components and how they interact.

This section highlights some simplifications in Bladed 3.85 that are improved in Bladed 4.0 as a result of moving to the Multibody dynamics structural model.

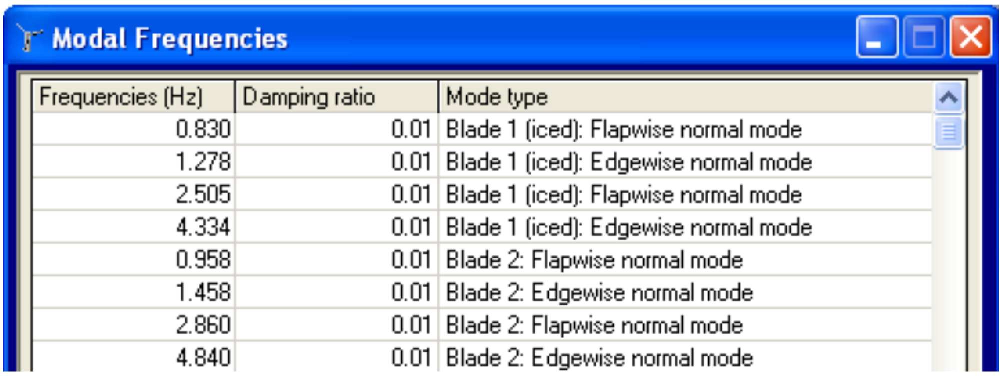
2.1.1 Rotor modes vs Individual blade modes

To model the blade dynamics, Bladed 3.85 uses rotor modes. Rotor modes are coupled modes for the rotor that involve motion in all of the blades. These modes are pre-calculated before the simulation starts for various pitch angles. A disadvantage of this approach is that it is not valid for cases where the pitch angle is different between the blades, for example when using individual pitch control or in blade fault cases.

Bladed 4.0 calculates individual blade modes at the start of the simulation. The modes are coupled together at each time step in the simulation, taking into account each blade’s pitch angle. This means that Bladed 4.0 can rigorously calculate the turbine dynamics even when the blade pitch angles are different.

An important advantage of individual blade modes is that the calculated modes contain coupled flapwise and edgewise motion. This tends to increase the damping in the edgewise direction and reduce edgewise fatigue loads, particularly towards the outer part of the blade.

Use of individual blade modes also allows the inclusion of different mass distributions for each blade. An example usage of this is to define different masses of ice on each blade, for cold climate calculations. The effect on the blade structural frequencies from icing can be captured in the individual mode shapes and frequencies, as illustrated in Figure 2-1.



Modal Frequencies

Frequencies (Hz)	Damping ratio	Mode type
0.830	0.01	Blade 1 (iced): Flapwise normal mode
1.278	0.01	Blade 1 (iced): Edgewise normal mode
2.505	0.01	Blade 1 (iced): Flapwise normal mode
4.334	0.01	Blade 1 (iced): Edgewise normal mode
0.958	0.01	Blade 2: Flapwise normal mode
1.458	0.01	Blade 2: Edgewise normal mode
2.860	0.01	Blade 2: Flapwise normal mode
4.840	0.01	Blade 2: Edgewise normal mode

Figure 2-1: Effect on modal frequency of blade icing mass

Figure 2-2 illustrates the different approach to modal inputs to and outputs from the modal analysis in Bladed 3.85 and 4.0.

Bladed 3.85 Bladed 4.0

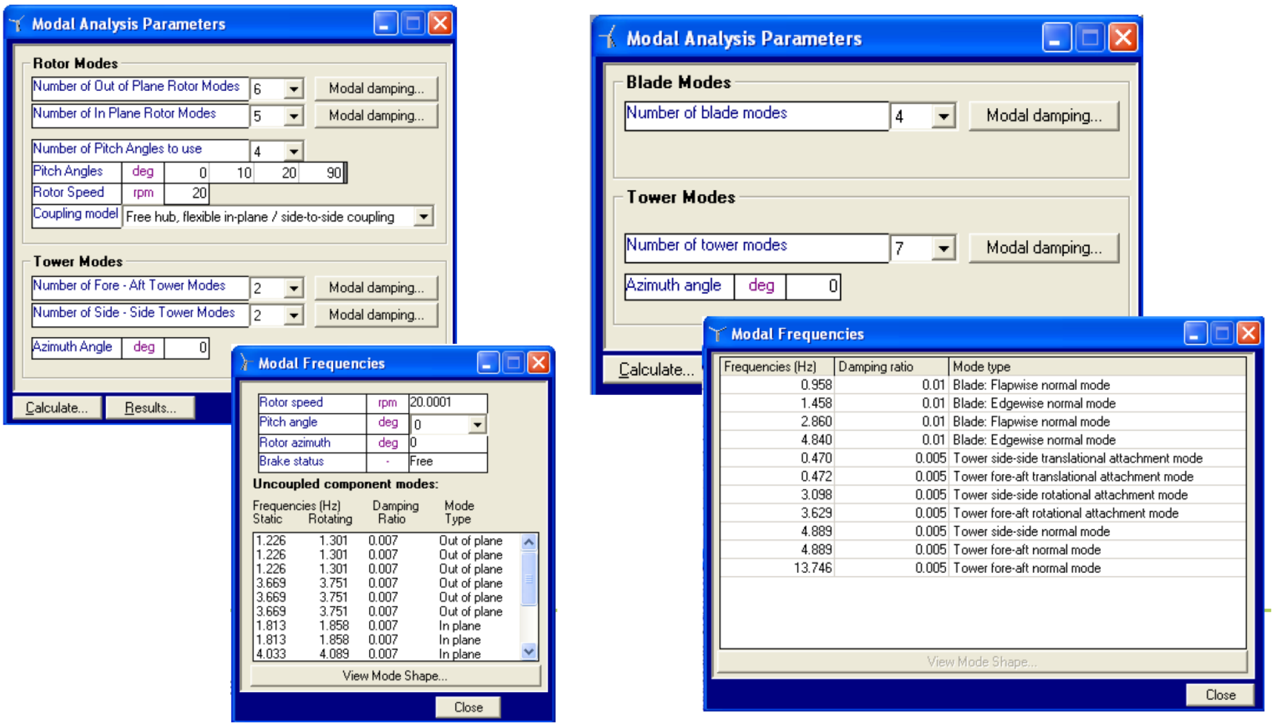


Figure 2-2: Blade and tower mode definition in Bladed 3.85 and 4.0

2.1.2 Blade torsional DoF

Bladed 3.85 does not allow torsional flexibility of the blade structural elements. As a result, a pure blade torsional mode cannot be calculated in 3.85. Accounting for blade torsional flexibility is becoming increasingly important for larger blades, where some blade designs can experience torsional stability problems.

Bladed 4.0 allows torsional flexibility of the blade elements. This means that torsional blade modes can be calculated, and their effect on aero-elastic stability be accounted for.

2.1.3 Shear centre offset from neutral axis

From Bladed 4.0, it is possible to define a translational offset between the neutral axis and the shear centre within the blade section, as illustrated in Figure 2-3. This is important to account for the torsional behaviour of non-standard structural section shapes such as aerofoils.

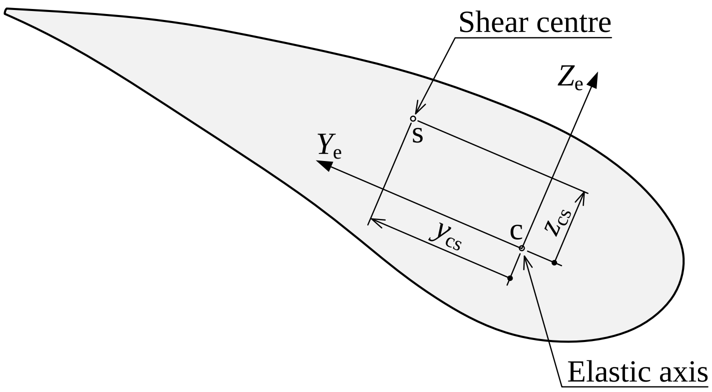


Figure 2-3: Shear centre offset from neutral axis

If the elastic centre and shear centre coincide, the constitutive relationship between strain and load for a beam element can be expressed as a diagonal matrix as shown.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \left[\begin{array}{ccc|ccc} EA & & & & Symm & \\ 0 & GA_y & & & & \\ 0 & 0 & GA_z & & & \\ \hline 0 & 0 & 0 & GI_x{}^* & & \\ 0 & 0 & 0 & 0 & EI_y & \\ 0 & 0 & 0 & 0 & 0 & EI_z \end{array}\right] \begin{bmatrix} \gamma_x \\ \gamma_y \\ \gamma_z \\ \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$

The effect of shear centre offset is to introduce additional coupling between shear forces and torsional moment, resulting in the following constitutive relationship around the neutral axis.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \left[\begin{array}{ccc|ccc} EA & & & & Symm & \\ 0 & GA_y & & & & \\ 0 & 0 & GA_z & & & \\ \hline 0 & -z_{cs}GA_y & -y_{cs}GA_z & GI_x & & \\ 0 & 0 & 0 & 0 & EI_y & \\ 0 & 0 & 0 & 0 & 0 & EI_z \end{array}\right] \begin{bmatrix} \gamma_x \\ \gamma_y \\ \gamma_z \\ \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$

where

$$GI_x = GI_x{}^* + GA_y z_{cs}^2 + GA_z y_{cs}^2$$

And $GI_x{}^*$ is the torsional stiffness defined around the shear (torsional) axis.

2.1.4 Lumped blade pitch inertia

In Bladed 3.85, the whole blade pitch inertia is lumped onto the blade root. This means that the pitch inertia is constant during the simulation. In reality, the blade pitch inertia is strongly affected by blade deflection during the simulation and so is not constant. This can have a significant effect on blade root torsional and pitch actuator loads.

In Bladed 4.0, the pitching inertia of the blade is calculated from the mass and inertia definition on the blade. The inertia is distributed along the blade, meaning that its contribution to loads along the blade can be accounted for. Torsional loads at the blade root take account of the deflected position of the blade, so the pitch inertia varies correctly during the simulation. This can have a significant effect on blade root torsional load and pitch actuator loads.

This difference in calculation of the blade pitch inertia is illustrated in Figure 2-4. This figure illustrates the distribution of mass and inertia along the blade and shows how the deflection of the blade mass at each time step is accounted for when calculating the internal load and blade pitch inertia (used for pitch actuator calculations).

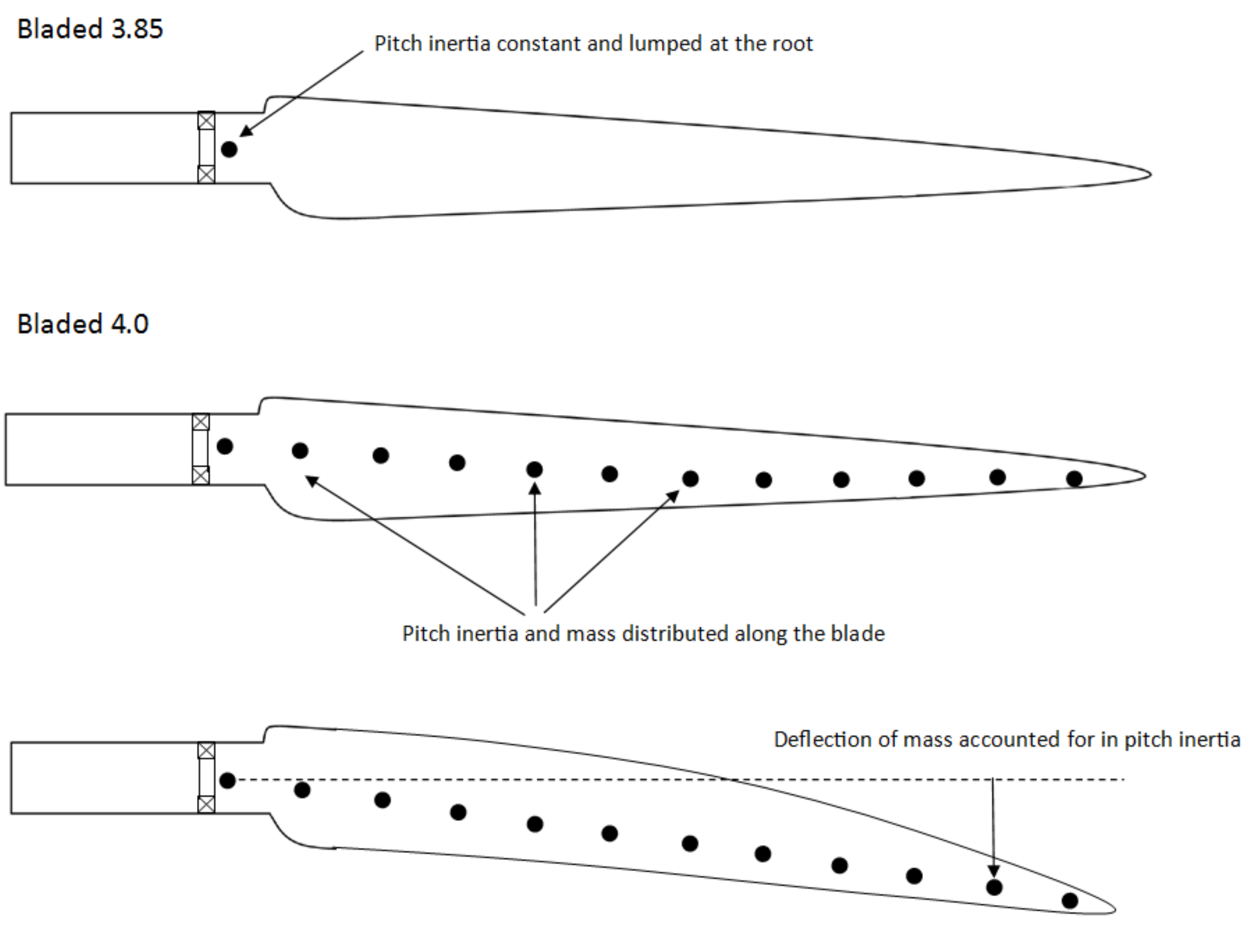


Figure 2-4: Blade pitch inertia in Bladed 3.5 and 4.0

This improved model of distributed blade mass and inertia can have a significant effect on the blade torsional (M_z) loads. An example comparison of blade root extreme torsional loads between Bladed 3.85 and Bladed 4.0 is shown in Figure 2-5, taken from [1].

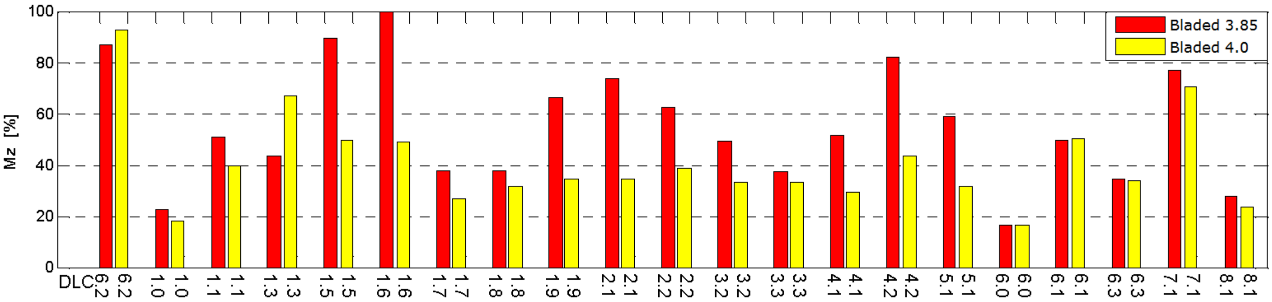


Figure 2-5: Example blade root extreme torsional load in Bladed 3.85 and Bladed 4.0

2.1.5 Limited blade output coordinates

In Bladed 3.85, the blade z-axis for load output is always parallel to the pitch axis, irrespective of the local orientation of the blade section. This means that the load output coordinate system is not fixed relative to the blade.

From Bladed 4.0, blade loads are reported in the principal axes coordinate system, which follows the deflected shape of the blade. This means that the blade load output coordinate system is fixed relative to the blade section. This is important to achieve useful load outputs when blade deflections are significant. This difference is illustrated in Figure 2-6. Note that in Bladed 4.0, the y-axis can be chosen to be along the chord or untwisted.

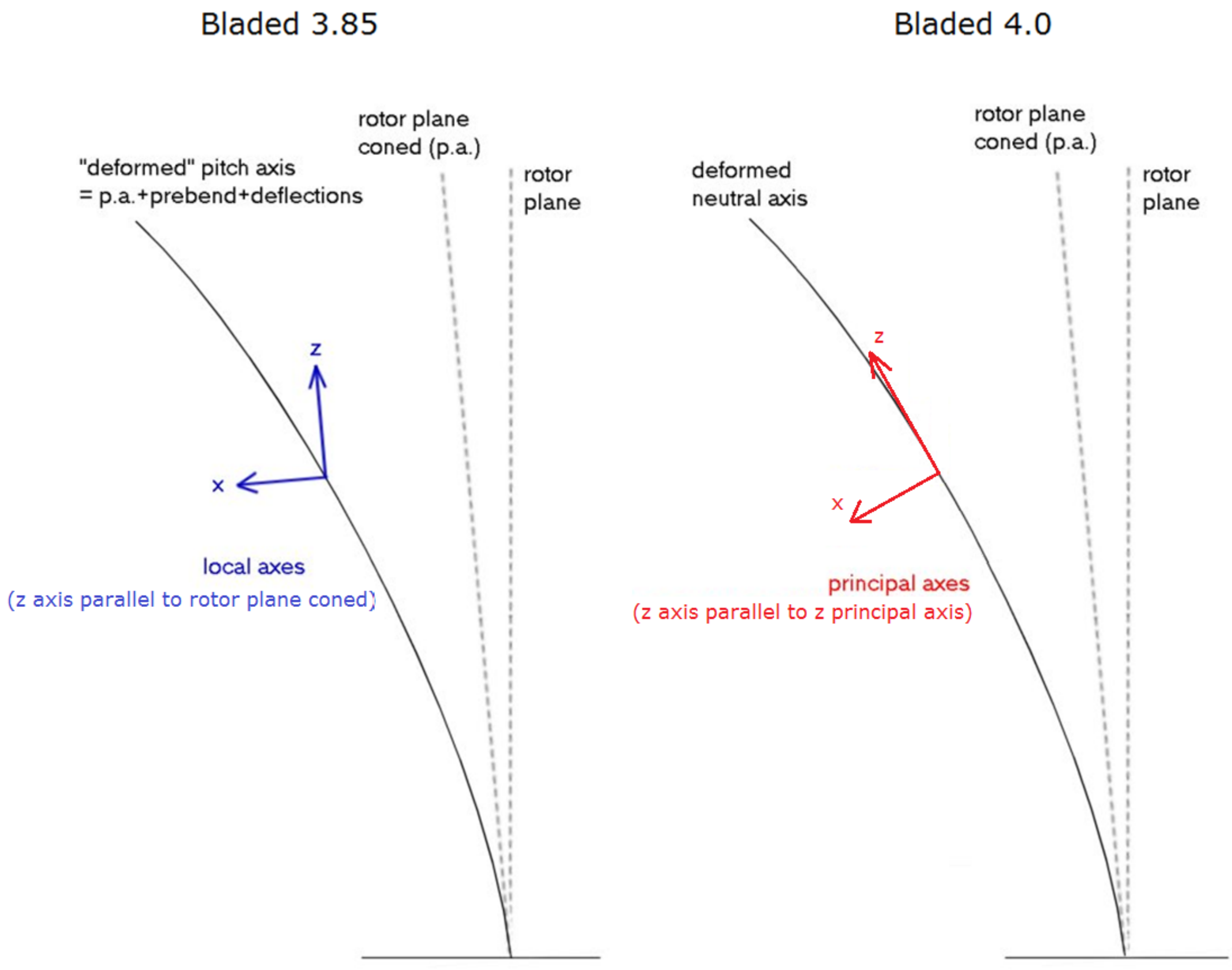


Figure 2-6: Blade load output coordinates in Bladed 3.85 and 4.0

2.2 Bladed 4.1

This section explains the blade modelling improvements in Bladed 4.1.

2.2.1 New blade output options

In Bladed 4.1, additional blade load output options of "Root Axes", "Aerodynamic Axes" and "User Axes" were added. Figure 2-7 illustrates the Aerodynamic and Root Axes compared to the Principal Axes. Note that the Bladed 4.1 "Root Axes" are equivalent to the Bladed 3.85 "local axes" load output coordinate system.

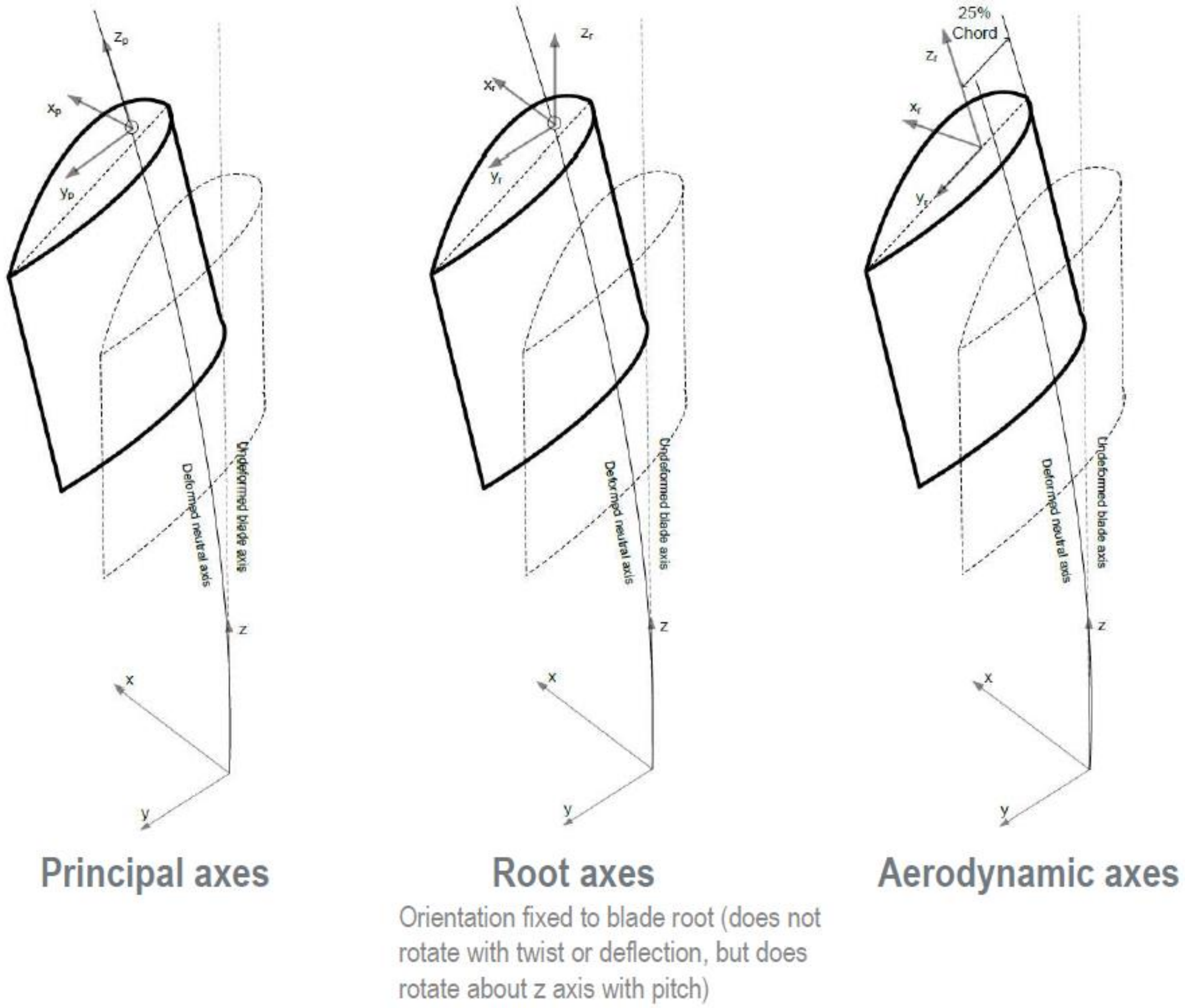


Figure 2-7: Principal, root and aerodynamic axes

The "User Axes" output was also added in Bladed 4.1. This allows the user to specify a location within the aerofoil at which to output blade loads, as illustrated in Figure 2-8. The user can specify whether the z-axis is parallel to the root axis or the local neutral axis, and independently whether the y-axis is aligned to the principal axis orientation or to the root axis.

For further details of all blade output coordinate systems, please refer to the Bladed User Manual (section 7.22).

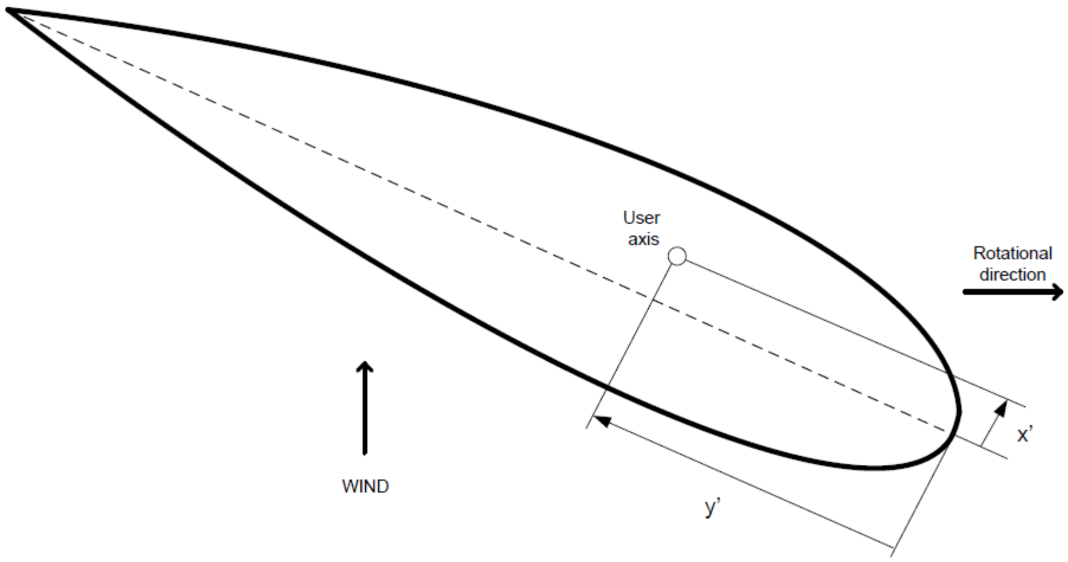


Figure 2-8: Definition of User Axes output coordinates from Bladed 4.1

2.2.2 Pitch bearing part-way along the blade

From Bladed 4.1, it is possible to define a pitch bearing part-way along the blade, as illustrated in Figure 2-9. This structural arrangement is sometimes used to reduce pitch bearing or pitch actuator duty.

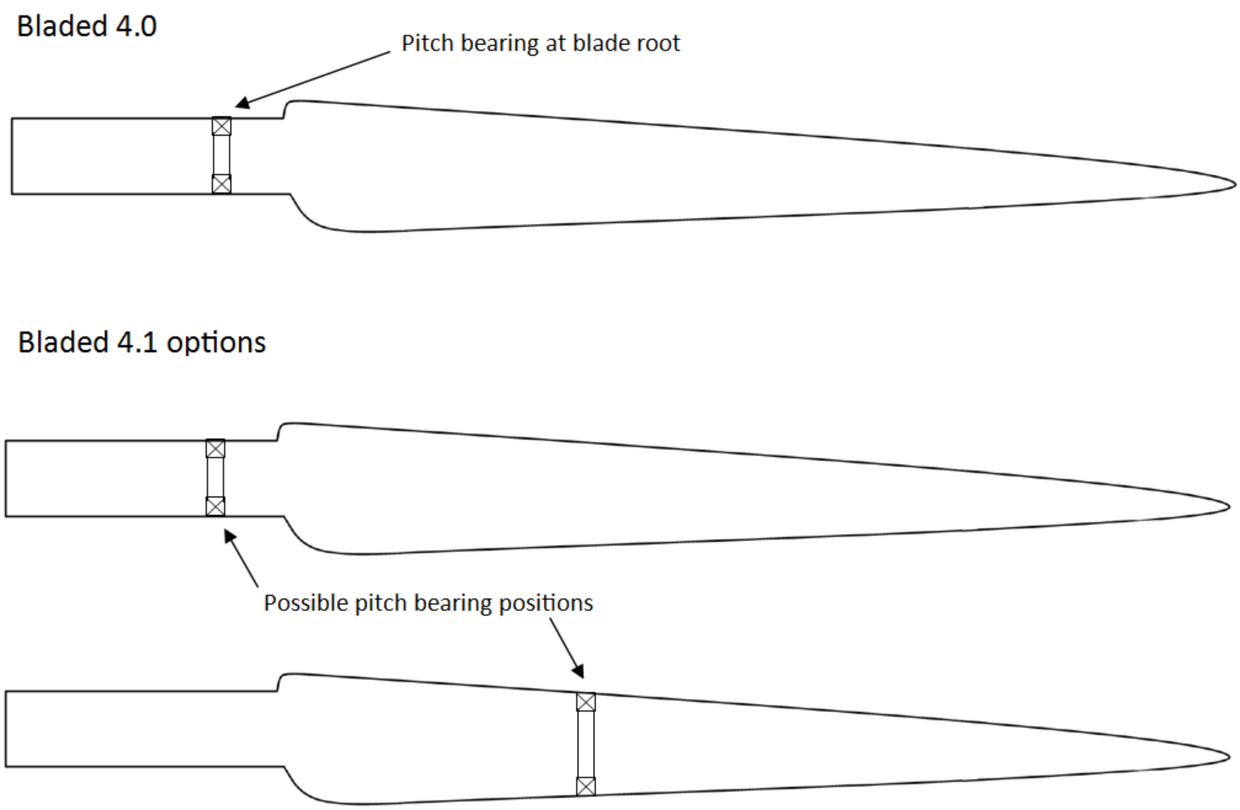


Figure 2-9: Possible pitch bearing positions in Bladed 4.0 and 4.1

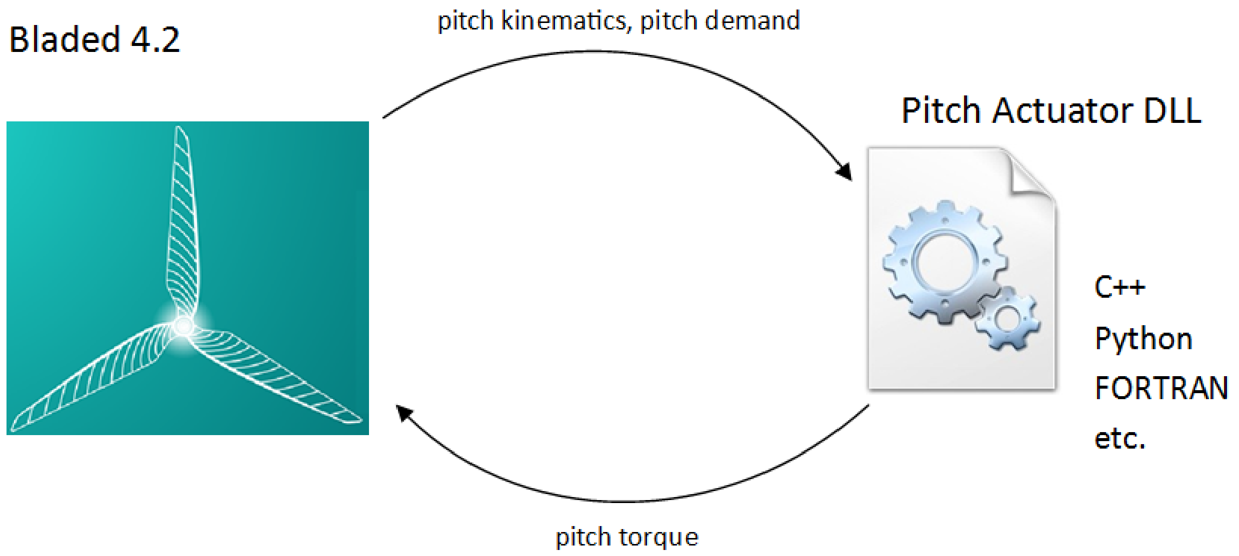
2.3 Bladed 4.2

This section explains the blade modelling improvements in Bladed 4.2.

2.3.1 Pitch actuator modelled as DLL

In Bladed 4.2, the Advanced Pitch actuator interface module was released.

This allows Bladed simulations to include user-defined pitch actuator dynamics of arbitrary complexity. The pitch actuator models can be coded in any convenient language and are linked to Bladed through a well-documented DLL interface. The pitch actuator model can be non-linear and time-varying and may include discontinuities, for example frictional stick-slip and backlash.



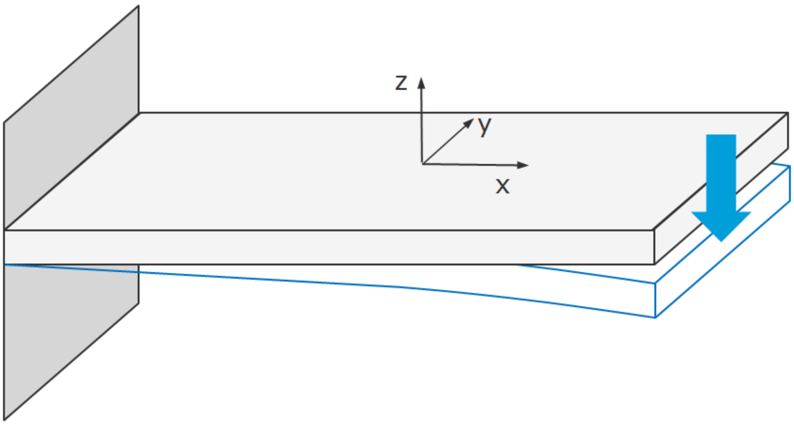
2.4 Bladed 4.3

This section explains the blade modelling improvements in Bladed 4.3.

2.4.1 Bend-twist coupling

From Bladed 4.3, the user can specify explicit bend-twist coupling terms in the blade definition. This is useful for modelling the behaviour of laminate layers in composite blades.

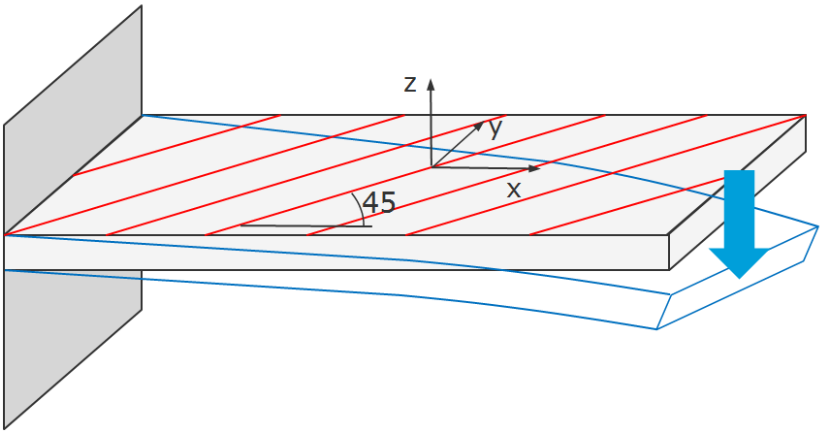
In Bladed 4.2 and earlier, the relationship between beam curvature and bending moment is described by a diagonal matrix, as shown in Figure 2-10.



$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} GI & 0 & 0 \\ 0 & EI_y & 0 \\ 0 & 0 & EI_z \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$

Figure 2-10: Curvature to bending moment relationship in Bladed 4.2

In Bladed 4.3, off-diagonal terms can be specified in this matrix, resulting in coupling between the beam element bending and twisting, as illustrated in Figure 2-11. The red lines illustrate laminate layer orientation. The user is able to specify the values of C_{xy} , C_{xz} and C_{yz}.



$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} GI & C_{xy} & C_{xz} \\ C_{xy} & EI_y & C_{yz} \\ C_{xz} & C_{yz} & EI_z \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$

Figure 2-11: Curvature to bending moment relationship in Bladed 4.3

2.4.2 Multi-blade coordinate transformation

In Bladed 4.3, the Campbell diagram calculation was extended so that the user can calculate coupled rotor modes in the non-rotating frame of reference. This is achieved through a "multi-blade coordinate transformation". Further details of this transformation are available in the Bladed Theory Manual (Section 3.6).

Using this transformation, the Campbell diagram includes

- Forwards and backwards whirling modes (sine and cosine cyclic modes)
- Coupled modes that are independent of azimuth angle (collective rotor modes)

It's important to be able to calculate the Campbell diagram in the stationary frame as this characterises the loading that the tower will experience loading from the rotor. This allows proper consideration of the excitation frequencies for the turbine design.

A Campbell diagram in the rotating frame of reference is shown in Figure 2-12. This form of the Campbell diagram can be calculated in all Bladed versions.

From Bladed 4.3, a Campbell diagram can be calculated in the stationary frame. A typical output is illustrated in Figure 2-13.

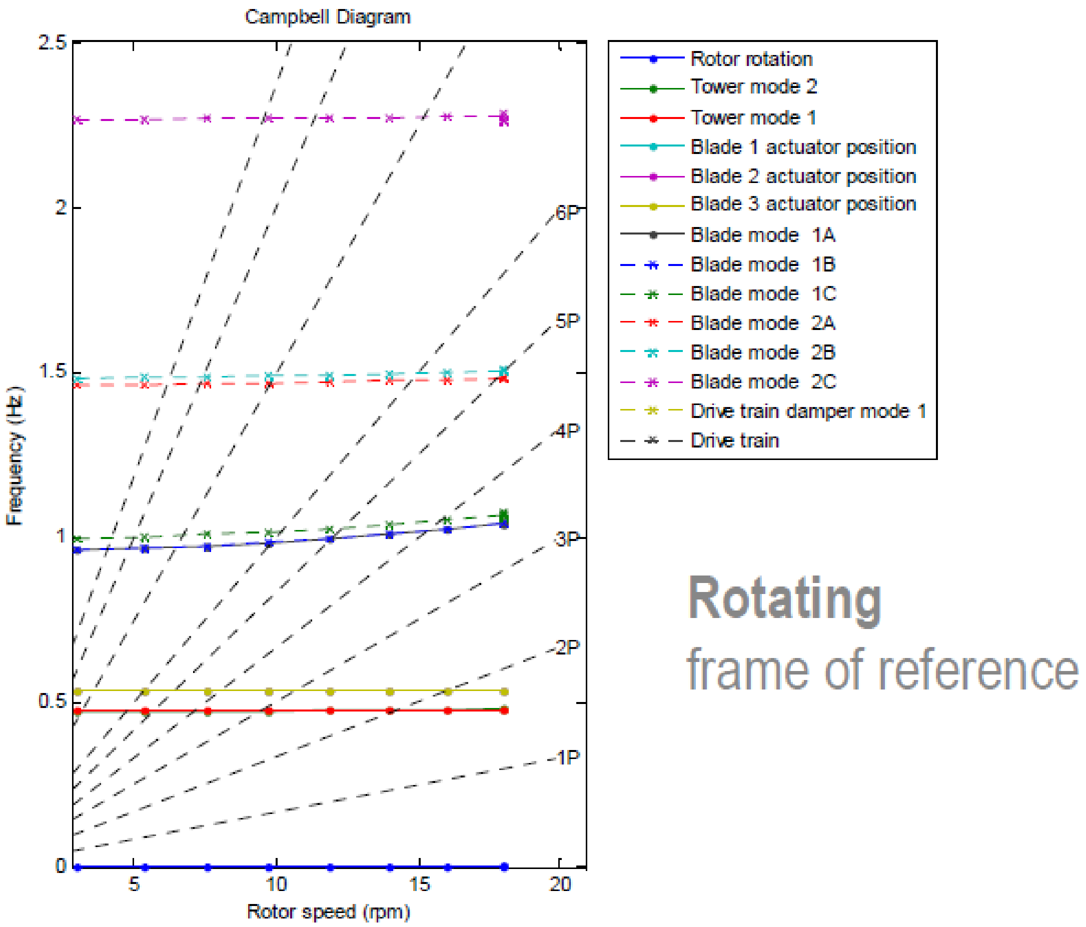


Figure 2-12: Campbell diagram in rotating frame of reference (all Bladed versions)

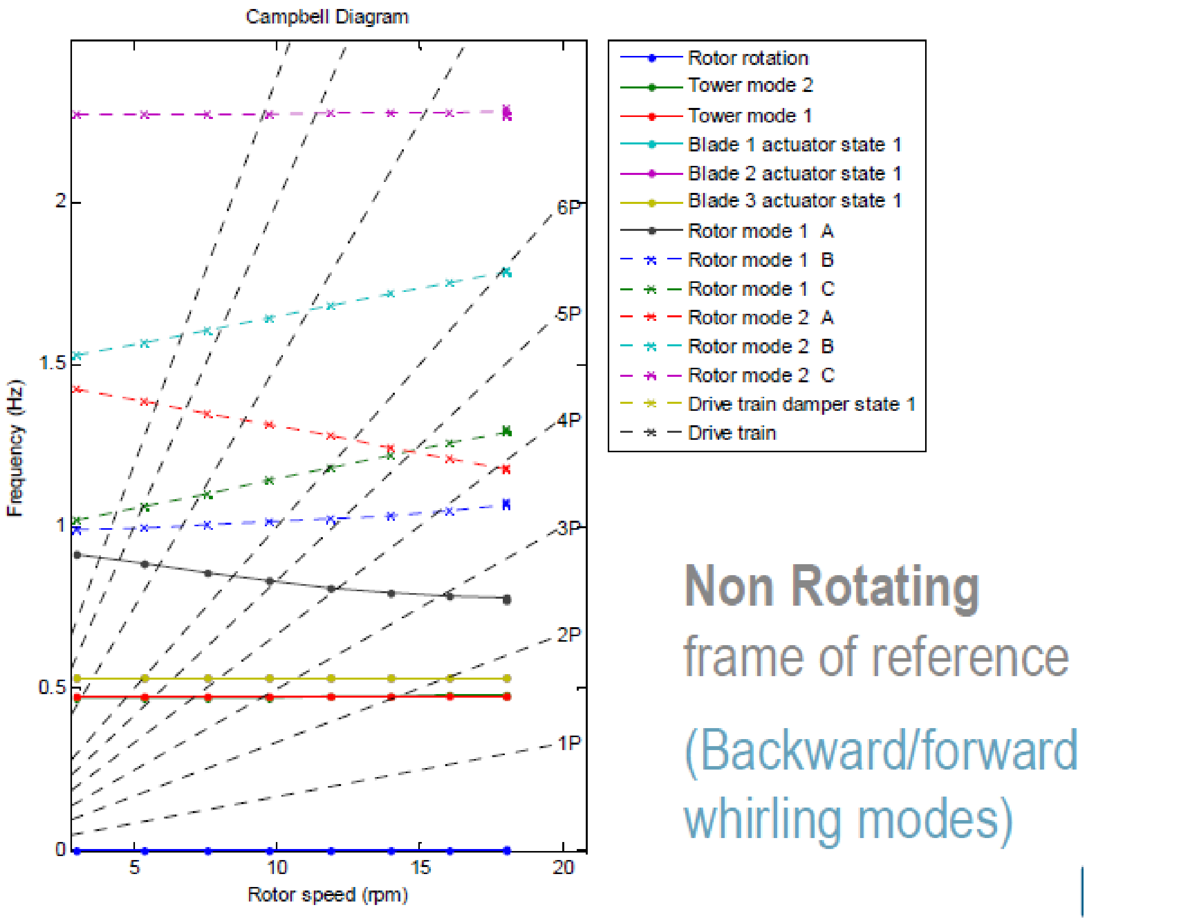


Figure 2-13: Campbell diagram in the stationary frame of reference (from Bladed 4.3)

2.4.3 Improved Beddoes Leishman dynamic stall

In Bladed 4.3, some improvements to the Beddoes Leishman dynamic stall model were implemented.

The most important change was the inclusion of a dynamic model for pitch moment coefficient (C_m), including the contribution from drag. This model is important for evaluating the torsional stability of blades, and is particularly important for accurate flutter prediction.

Further details on extensions to the Beddoes Leishman model in Bladed are detailed in the Bladed Theory Manual (section 2.4).

2.5 Bladed 4.4

This section explains the blade modelling improvements in Bladed 4.4.

2.5.1 Shear axis orientation relative to neutral axis

In Bladed 4.4, the blade structural model was improved to account for the *orientation* difference between the elastic axis and the shear axis. The elastic axis is the line along the beam element that connects the neutral axis positions at each station. The shear axis is the line along the beam element that connects the shear centre positions at each station.

In general the elastic and shear axes are not parallel, so it can be important to take account of the orientation difference between them. Note that the *translational* offset was already taken into account in previous Bladed versions as shown in Figure 2-3.

The orientation difference between the shear axis and the elastic axis is illustrated by the θ terms in Figure 2-14.

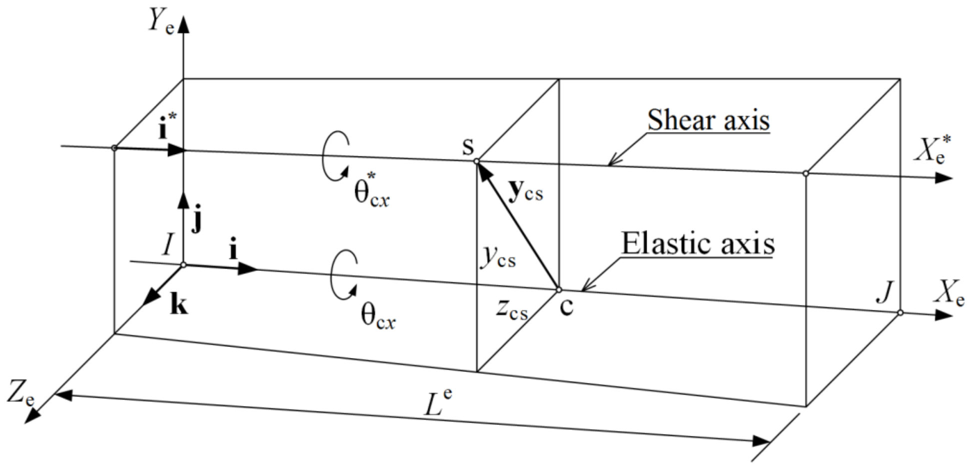


Figure 2-14: Orientation difference between shear and elastic axes.

The derivation of the effect of shear axis orientation is out of the scope of this document. A key effect is that it results in extra bend-twist off–diagonal coupling terms in the (previously diagonal) constitutive matrix that describes the relationship between beam element curvature and bending moment. The off-diagonal terms in the matrix below result from the orientation difference between the shear and neutral axes.

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} GI & & sym \\ -\dfrac{\Delta y_{cs} EI_y}{L} & EI_y & \\ -\dfrac{\Delta z_{cs} EI_y}{L} & 0 & EI_z \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$

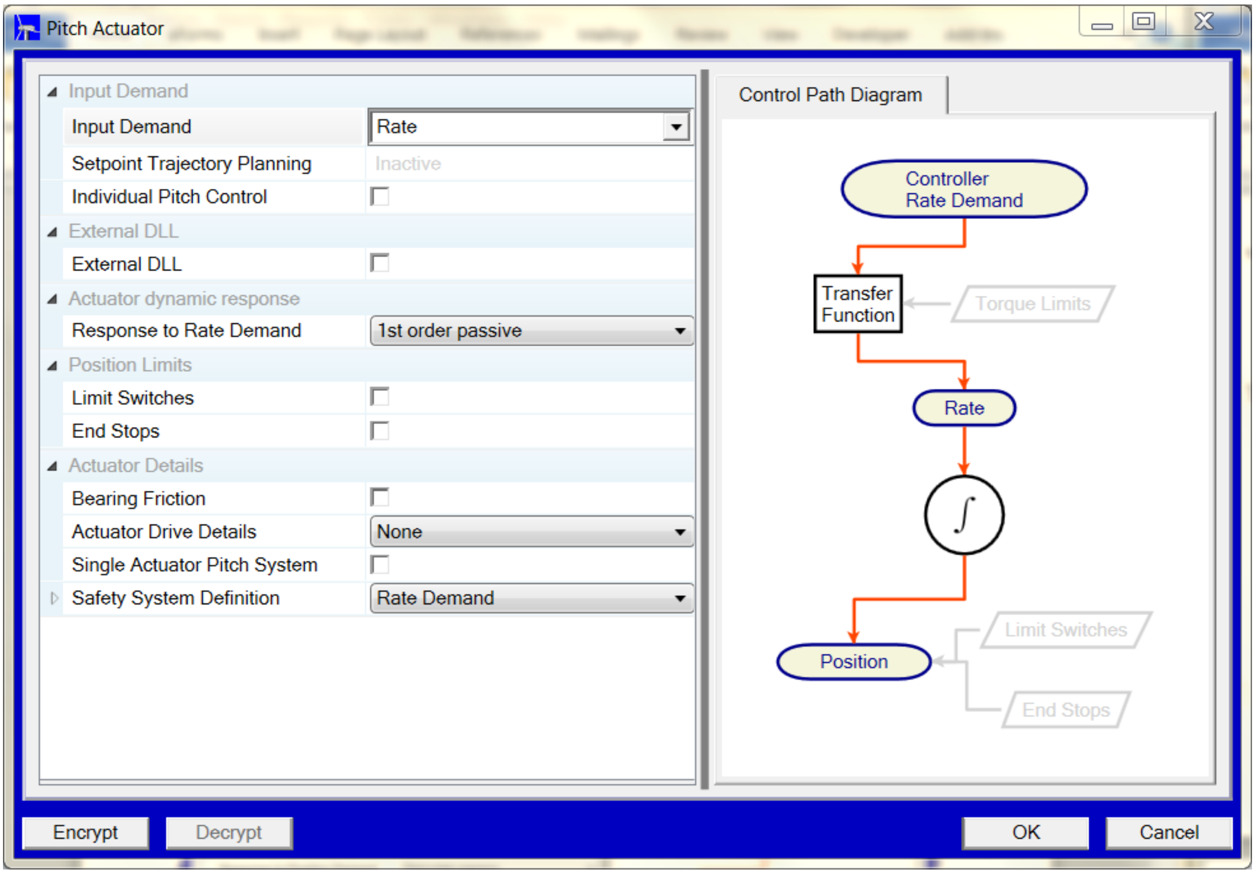
where Δy_{cs} and Δz_{cs} show the change in shear centre offset along the element. Further details are available on request from DNV GL.

2.5.2 New pitch actuator model and User Interface

A new pitch actuator model and new User Interface were written for Bladed 4.4. Some new features introduced by the new pitch actuator model are

- **Pitch rate dependent torque limits**: This is important to properly characterise the available torque from a pitch actuator when operating at different pitch rates.
- **Torque limits** can be defined and **pitch actuator torque** can be viewed in all pitch actuator systems. In 4.3, these are not available when the actuator has a passive response to position demand.
- **Independent torque limits** can be defined for **safety system** pitch action.
- **Rotary actuator flexibility:** Torsional flexibility of the actuator system can now be modelled.
- **Pitch limit switches:** Define pitch angle limits beyond which the actuator torque is removed and the pitch brake is applied.
- **Pitch end stops:** Define pitch angle limits that define the location of physical pitch end stops, and specify the end stop stiffness.

The Bladed 4.4 pitch actuator screen is one of the first Bladed screens to use the new modern Bladed User Interface style, including dynamically updating diagrams.



Full details of this pitch actuator model are available in the Bladed Theory Manual (section 5.6).

2.5.3 Extra User Axes outputs (align to Aero axes)

From Bladed 4.4, the User Axes load outputs were extended to allow the y-axis direction to be aligned into 3 different directions, as illustrated in the screenshot from the Bladed blade screen in Figure 2-15.

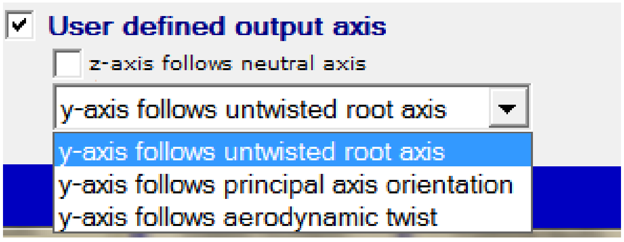


Figure 2-15: User Axes output options from Bladed 4.4

2.6 Bladed 4.5

This section explains the blade modelling improvements in Bladed 4.5.

2.6.1 Application of point loads to blades

In Bladed 4.5, it is possible to apply point loads time histories to the blade. This feature can be used to examine the deflection of the blade given certain loading, or to model impacts on the blade. The point loading time history is defined in an external text file.

2.6.2 New geometric stiffening model

A new geometric stiffening model was introduced in Bladed 4.5 that accounts for the extra loads generated when *shear* forces are applied to a blade in its deflected position. This was referred to as the "full" geometric stiffness model.

Note that **this model was deprecated in Bladed 4.5.0.115, 4.6.0.120 and 4.7.0.93** as it was it was found to be less accurate and stable than the default geometric stiffness setting in Bladed 4.4. The default geometric stiffness settings in Bladed 4.0-4.7 are now identical across all versions. The default setting is "axial only" geometric stiffness. Full details of these changes to geometric stiffness settings are available in [02].

2.7 Bladed 4.7

This section explains the blade modelling improvements in Bladed 4.7.

2.7.1 Multi-part blade

Bladed 4.7 includes a "multi-part blade" feature, whereby blade non-linear deflections are more rigorously modelled by splitting the blade into several linear finite element components. Full details of how to use this feature are given in [3].

2.7.1.1 Whole blade as one finite element body

By default in Bladed, the whole blade is modelled as a single finite element body, and linear mode shapes are calculated for the whole blade. This method gives a good representation of small blade deflections. A whole-blade linear mode shape is illustrated in Figure 2-16.

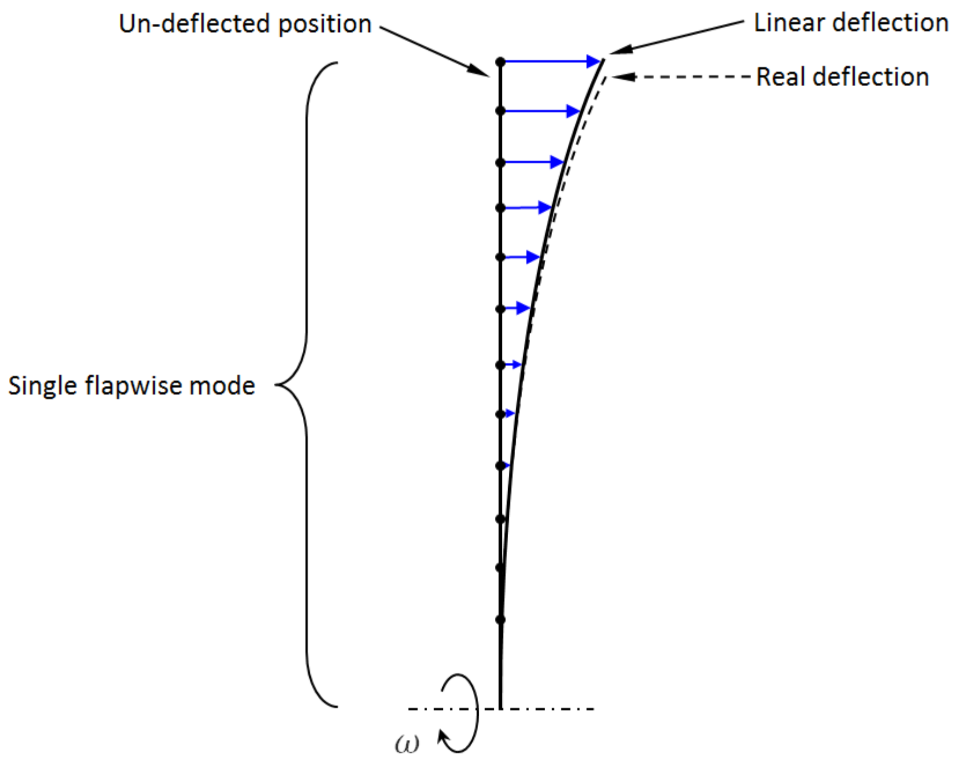


Figure 2-16: Blade modelled as a single linear finite element body

Some disadvantages of this approach are

- Mode shapes are only valid for small deflections
- Change in radial position due to deflection is not accounted not accounted for
- Modelling of blade torsion resulting from bend-twist coupling is not accurate

As blade lengths are increasing and blades are becoming more flexible, blade deflections are becoming larger, with tip deflections greater than 15% of the blade length. A single linear finite element body cannot accurately describe the deflected position of a blade undergoing such large deflection.

2.7.1.2 Several finite element bodies for each blade

In Bladed 4.7, it is possible to model the blade as several connected finite element bodies, in order to more accurately account for large blade deflections.

Figure 2-17 shows a blade modelled using two linear finite element bodies. The outer section is able to undergo *large* rotations, allowing the positions of the blade subject to large deflections to be calculated more accurately. Each individual blade part undergoes a smaller deflection, so the small deflection assumption when calculating mode shapes is more valid. It is possible in Bladed 4.7 to split the blade into any number of linear sections.

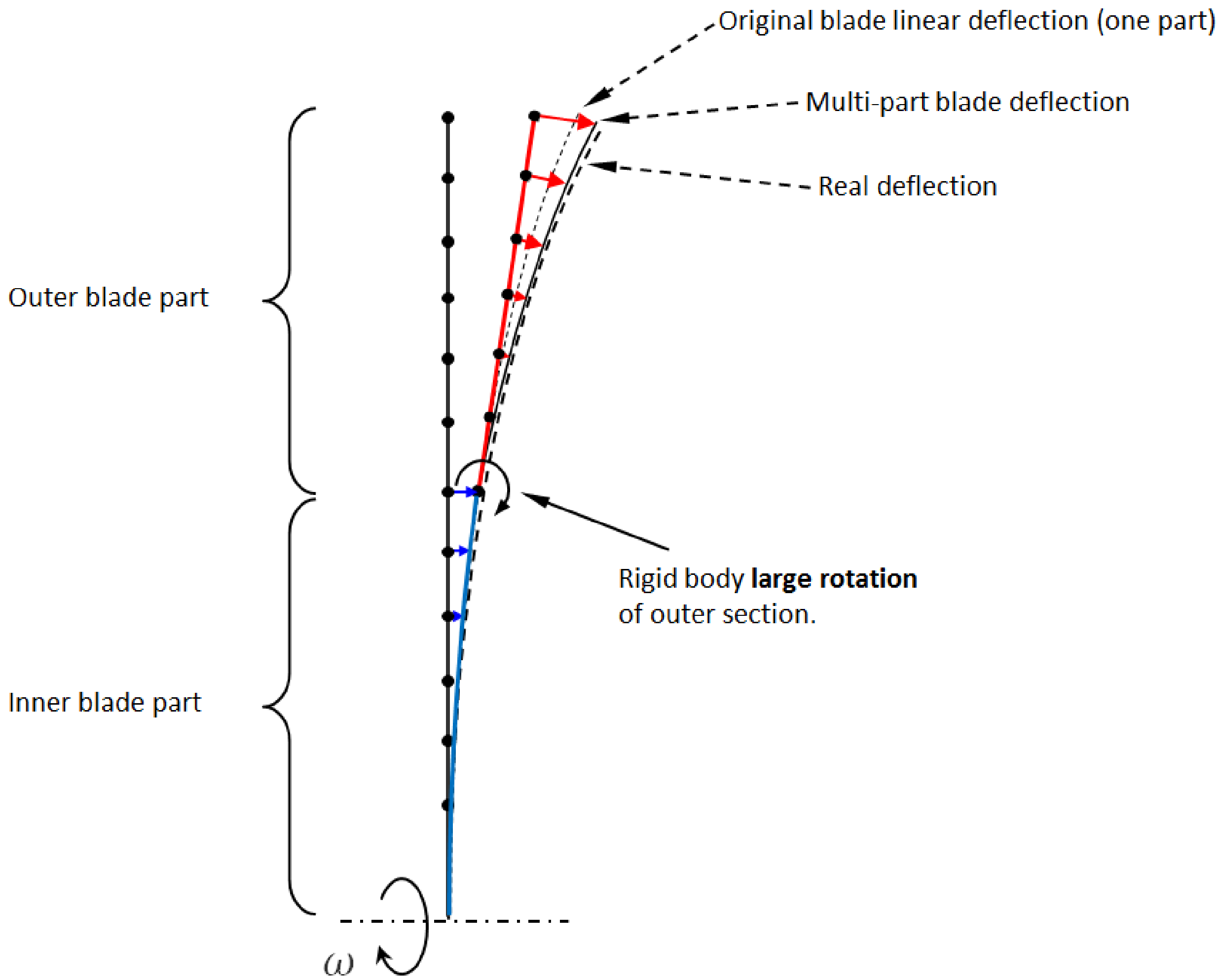


Figure 2-17: Blade modelled using two linear finite element bodies

REFERENCES

1. *Bladed Multibody Validation*, GL Garrad Hassan report 1042/BR/01
2. *Geometric stiffness options in Bladed 4.3 - 4.7*, DNV GL report 110052-UKBR-T-22
3. *Multi-part blade beta: User Guide for Bladed 4.7,* DNV GL report 110052-UKBR-T-27