Multi-Part Blade Beta: User Guide for Bladed 4.7

Author: Will Collier

Checked: Philip Bradstock

Issue: F

Date of issue: 16 March 2016

Updates in issue F

- Added section on Generalised Alpha integrator

Doc no: 110052-UKBR-T-27-F

1 SUMMARY

This document summarises the theory and use of the multi-part blade feature, available in beta in Bladed 4.7. Please use Bladed 4.7.0.88 or later.

The multi-part blade feature divides the blade into any number of linear "parts", allowing the blade structural model to be non-linear. This is an important feature for modelling long flexible blade designs, especially in terms of the blade torsional behaviour and stability.

2 THE MULTI-PART CONCEPT

2.1 Whole-Blade Linear Blade Modes

The default approach used in Bladed to model the blade flexibility is to model the blade as a single linear finite element body. Several linear mode shapes that include deflections of the whole blade are calculated to account for blade deflection. This is illustrated in Figure 2-1.

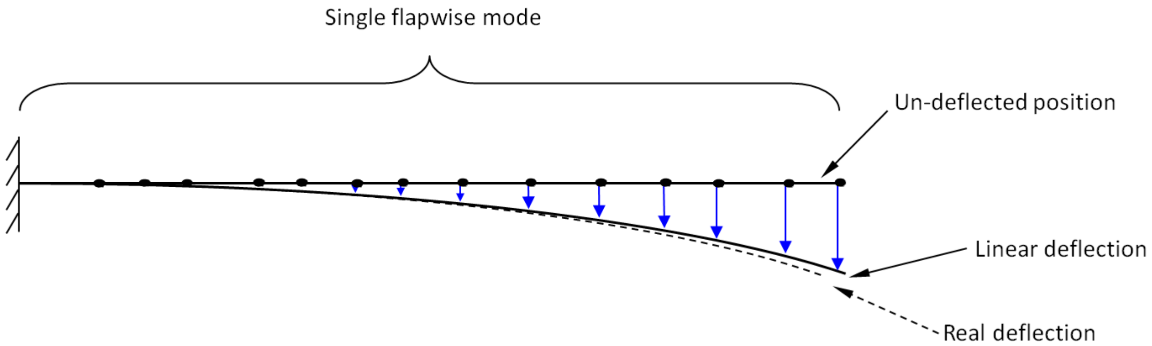


Figure 2-1: Linear blade model

Using whole-blade linear modes results in fast simulations as the number of degrees of freedom to model the blade deflections is small, and the freedom frequencies are relatively low. This approach often gives an accurate representation of blade dynamics. However, for this approach to be valid, the deflections of the blade must be small.

Many modern blade designs are very flexible, meaning that the small deflection assumptions in the linear model become less valid. This can lead to inaccuracies in predicting the blade dynamic response, in particular the blade torsion.

2.2 Multi-part Blade Model

One method to maintain the small angle assumption for the blade modes is to split the blade into several linear parts. Figure 2-2 shows a schematic of modelling a blade using two linear parts.

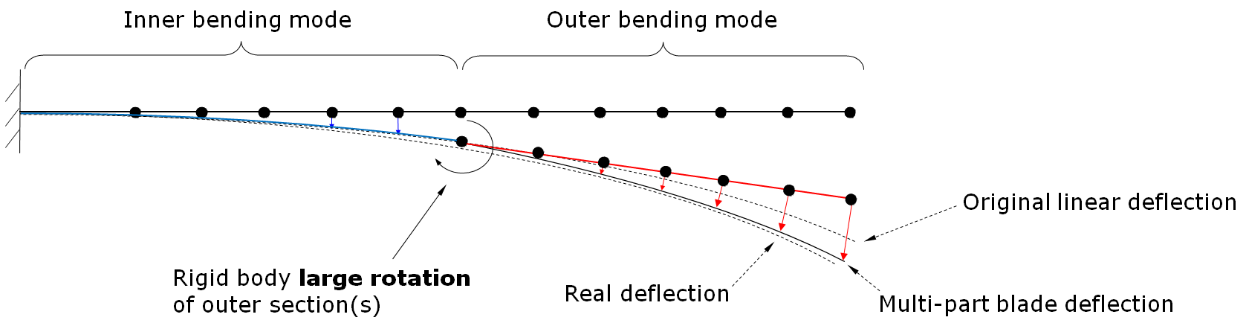


Figure 2-2: Non-linear wind turbine blade model using two linear parts

The outer blade part can undergo a rigid body rotation based on the deflection and rotation of the inner part, as well as including linear mode deflections. The deflections within each linear part are therefore smaller than if using a single linear blade part. Splitting the blade into several parts allows for non-linear load transfer between each linear part, and a more accurate model of the blade deflection.

3 DEFINING MULTI-PART BLADES IN BLADED

This section describes how to define the multi-part blade properties in Bladed.

3.1 Project Info Code

In Bladed 4.7, the multi-part blade feature is accessed through "Project Info". The following syntax defines the recommended settings to define a multi-part blade in Bladed and achieve good simulation speed.

The first block of code is compulsory, and the other sections are recommended default settings. The function of each block of code in explained in this section 3 and 4.

```
MSTART EXTRA
NumberOfBladeParts  3                 * Number of blade parts
MultiPartSplitStations  1  10  17  22  * Stations where the blade is split including the root and tip
MultiPartNumberOfModes  8 8 8          * Number of modes on each part
NumCoupledModeDampingValues 6         * Number of coupled modes where damping is specified
MultiPartCoupledModeDamping 0.007 0.007 0.007 0.007 0.007 0.007 * coupled mode damping ratios
MEND

MSTART EXTRA
GenAlphaMethod 1                      * Activates the generalised alpha integrator method
RoInf 0.8                             * Value of spectral radius at infinite frequency
MaxIt 1
MEND

MSTART EXTRA
NumberSolveSystemIterations 1         * Iteration setting when calculating state accelerations
ResetAccOnSetState Y                  * Flag to reset accelerations to 0 for geometric stiffness model
MEND

MSTART EXTRA
BLADEGEOMSTIFF 5                      * Recommended setting for geometric stiffness. See [3]
MEND
```

3.2 Multi-part blade basic definition

The following code defines the blade split points, the number of modes on each blade part, and the structural damping.

```
MSTART EXTRA
NumberOfBladeParts  3                 * Number of blade parts
MultiPartSplitStations  1  10  17  22  * Stations where the blade is split including the root and tip
MultiPartNumberOfModes  8 8 8          * Number of modes on each part
NumCoupledModeDampingValues 6         * Number of coupled modes where damping is specified
MultiPartCoupledModeDamping 0.007 0.007 0.007 0.007 0.007 0.007 * coupled mode damping ratios
MEND
```

3.2.1 Number of parts and modes

As the number of blade parts is increased, the results (e.g. blade loads and deflections) will converge. More blade parts results in greater accuracy but greater simulation time. Typically 5 blade parts is enough for convergence, so this is may be a good starting point.

The number of modes on each part is an important parameter to ensure that the blade dynamic response is captured accurately. It is recommended to choose enough modes to include at least 5 attachment modes (to include a torsional mode) and 2 normal modes.

3.2.2 Specifying damping

When a blade is split into several linear parts, mode shapes are calculated for each linear part. In the Bladed modal structural dynamics formulation, modal damping must be specified for each mode on each blade part. However, in general the damping value for these individual modes would not be known by the blade designer, as these modes for the individual blade parts cannot be observed individually in reality to measure their damping.

To overcome this difficulty, Bladed calculates coupled modes for the multi-part blade by solving the Eigen solution for all of the blade parts together. The coupled modes are made up of contributions from the individual blade part modes. The coupled modes should have very similar shapes and frequencies to the usual whole-blade mode shapes found for a linear blade model, if enough modes have been specified on each part. Damping ratios can then be specified for the *coupled* blade modes, and Bladed will calculate the appropriate damping ratios for the individual blade parts, according to theory presented in [1], pp240-242.

The number of coupled modes for the blade is equal to the total number of modes on all of the blade parts. For example, for a blade split into 4 parts with 8 modes on each part, there are 32 coupled modes. The first few *coupled* modes should be familiar shapes (e.g. first flapwise mode) for which damping is usually known. Note that in general, it is not necessary for the user to specify damping for all of the coupled modes. Instead, damping should be specified for the coupled modes which would be expected to contribute significantly to the dynamic response of the blade (typically the first ~10 modes).

For subsequent higher frequency coupled modes, the damping is assumed to be proportional to modal stiffness, calculated as $\mathbf{C} = a_1\mathbf{K}$. This results in damping that is proportional to modal frequency, so that the responses of higher frequency modes are effectively eliminated by high damping ratios.

The coefficient a_1 is defined according to the highest mode for which damping *is* specified.

$$a_1 = \frac{2\xi_c}{\omega_c}$$

subscript c refers to highest mode with damping specified
ξ refers to the coupled mode damping ratio

Damping on these higher frequency coupled modes is given by

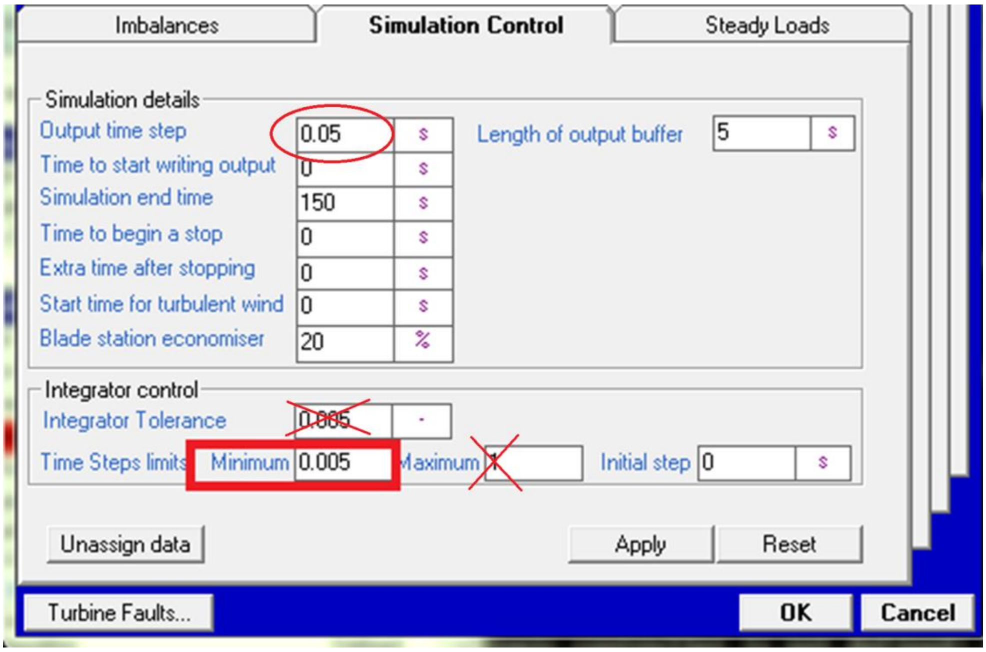
$$\xi_n = \xi_c\left(\frac{\omega_n}{\omega_c}\right)$$

Once the coupled mode damping values are calculated, the blade part modal frequencies are calculated in Bladed according to [1].

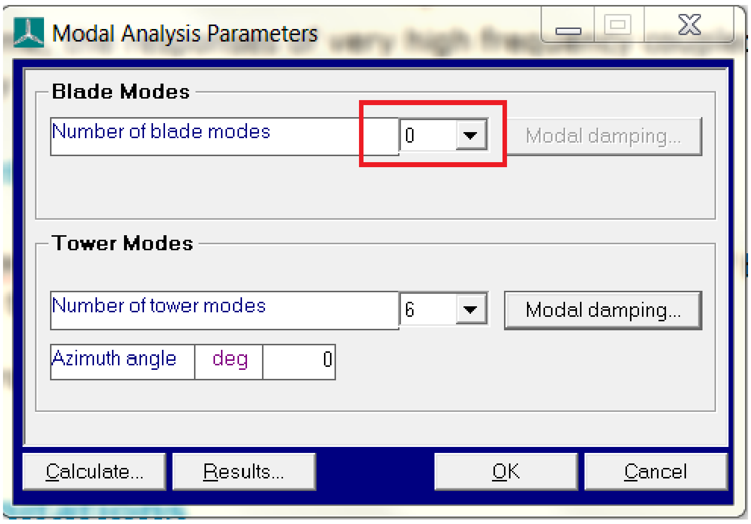
3.3 Other Practicalities

1. Recommended practice with multi-part blades is to use a fixed step integrator (either Newmark Beta or Generalised Alpha). The fixed step size must be specified in the *Simulation Control* screen in the 'minimum time step' field as shown below.

   The 'Integrator tolerance' and 'maximum time step' field are not used for fixed step integrators. Note that the "Output time step" must be a multiple of the integrator time step. Typically, stable simulation can be achieved with a step size of 0.005s.

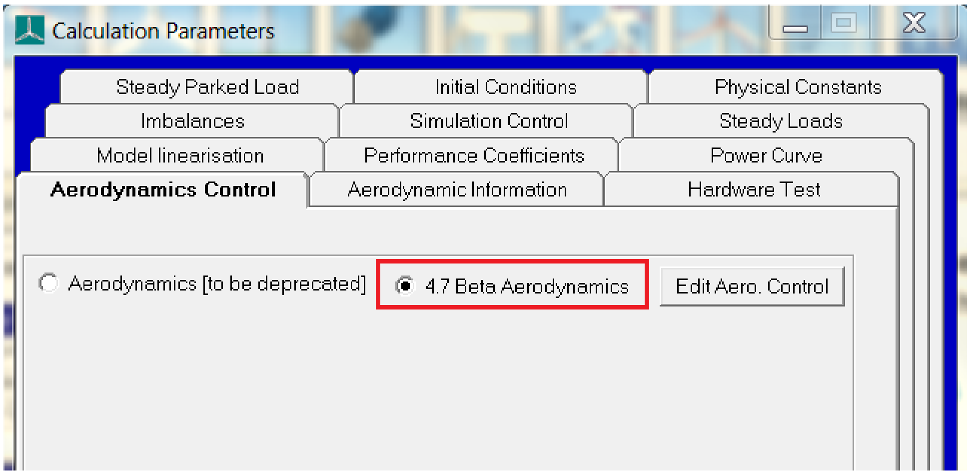


2. When using the multi-part blade Project Info code, the number of blade modes should be set to zero in the *Modal Analysis* screen.



   <u>Note that it is not possible to run a standalone Modal Analysis calculation</u> for a multi-part blade in Bladed 4.7. Instead, you must run a calculation (e.g. power production) and examine the contents of the $VE file.

3. The 4.7 Beta Aerodynamics must be enabled in the *Aerodynamics control* screen.



4. Remove any point masses from the blade definition. Blade point masses are not currently supported for multi-part blade.

5. Remove any blade load or deflection output locations that interpolate between blade nodes. Output between blade nodes is not currently supported.

4 IMPROVING MULTI-PART BLADE SIMULATION SPEED

Simulating a multi-part blade is in principle more computationally expensive than a single-part blade, due to a higher number of degrees of freedom and higher frequencies for each degree of freedom.

This section discusses some methods to increase the simulation speed for multi-part blade simulations.

4.1 Newmark Beta integrator

From Bladed 4.7.0.62, a Newmark Beta integrator is available in Bladed. The Newmark Beta method integrates the second order states in an explicit fashion (i.e. without iteration). To allow explicit integration, the integration makes use of the system mass and stiffness matrices.

The Newmark Beta method has an input parameter *Beta* that determines how the acceleration of each state is assumed to vary within an integrator step. Choosing a value of *Beta* = 0.25 results in constant acceleration across a time step, which gives unconditional stability when integrating linear systems. Although the wind turbine system is non-linear, this unconditional stability (for linear systems) means that a large fixed time step can be used for non-linear simulations, leading to improved simulation speed.

The Newmark Beta integrator can be activated with the following Project Info code:

```
MSTART EXTRA
NewmarkBetaMethod 2        * Newmark method. Must use a value of 2.
Beta 0.25                  * Newmark method beta value
Gamma 0.5                  * Newmark method gamma value
MaxIt 1                    * Number of iterations on prescribed and first order freedoms. Default 1.
MEND
```

The Newmark Beta method runs with a fixed time step, which must be specified in the *Simulation Control* screen as explained in section 3.3.

Typically, stable simulation can be achieved with a step size of 0.005s. The time step can be increased as to improve simulation speed. Care should be taken that the results with larger time step do not differ significantly from those obtained with a small time step. If the time step is too large then the integration will be inaccurate and the simulation may become unstable.

4.2 Generalised Alpha integrator

From Bladed 4.7.0.79, a Generalised Alpha integrator is available in Bladed. The Generalised Alpha integrator is very similar to the Newmark Beta algorithm, but with more favourable algorithmic damping properties.

The Generalised Alpha method [2] applies algorithmic damping to high frequency modes (which can cause numerical instabilities that don't appear in reality) whilst minimising the algorithmic damping applied to low frequency modes, which are most important to the blade structural response.

The addition of damping allows simulations to be run on a larger time step without significant loss of accuracy, resulting in a reduction in simulation time. The improvement in simulation time is most significant for blades with low structural damping values.

The damping is controlled by the *spectral radius at infinite frequency*, which can vary between 0 and 1. A value of 1 gives no algorithmic damping and is equivalent to Newmark Beta. A value of 0 results in very high damping at infinite frequency. A suggested starting value for Bladed simulations is 0.8.

The integrator is activated with the following code

```
MSTART EXTRA
GenAlphaMethod 1              * Activates the generalised alpha integrator method
RoInf 0.8                     * Value of spectral radius at infinite frequency
MaxIt 1
MEND
```

Any Project Info code related to Newmark Beta should be removed. The simulation time step is fixed and must be set in the same way as for the Newmark Beta model.

4.3 Model solving options

To enable time integration of the model, the system state accelerations are calculated at each time step, based on the current states (displacements and velocities) and the applied loads. Calculation of these accelerations is referred to as "solving" the model.

Geometric stiffness forces are calculated at each time step based on the modal structural deflection of flexible components and the internal member load. The internal member load is calculated based on the underlying finite element (FE) model deflections, rather than modal deflections.

To calculate the correct FE deflections at each time step, external applied loads as well as inertia loads are applied to the FE model. Strictly iteration is required, as the displacements depend on inertia forces, the inertia forces depend on the accelerations, and the accelerations depend on the displacements.

To avoid the need for iteration on each time step (and so improve simulation speed) the inertia forces can simply be set to zero for purposes to evaluating the internal loads used in the geometric stiffness forces. DNV GL internal studies have shown that the impact of this simplification on simulation accuracy is minimal for multi-part blades, but there is a significant improvement in simulation stability.

The following Project Info code sets the inertia forces to zero for the purposes of calculating the geometric stiffness forces, and also limits the number of iterations to 1 (i.e. no iteration).

```
MSTART EXTRA
NumberSolveSystemIterations 1     * Iteration setting when calculating state accelerations
ResetAccOnSetState Y              * Flag to reset accelerations to 0 for geometric stiffness model
MEND
```

5 MULTI-PART BLADE TROUBLESHOOTING

5.1 Numerical instabilities

If the blade is suffering from numerical instability, the following steps could be investigated to try to eliminate the instability.

1. Reduce the time step used for the Newmark Beta or Generalised Alpha integrator. The time step is fixed with this integrator so doesn't reduce when the integration gets more difficult (e.g. when there is a lot of high frequency excitation). If the time step is too large, numerical errors can build up and cause instability.

2. If using the Generalised Alpha integrator, trying reducing the value of the spectral radius at infinite frequency (*RoInf*). This will introduce algorithmic damping to the high frequency modes that may be causing instability. Note that some damping to lower frequency modes is also added.

3. Increase the damping specified on each coupled mode in Project Info.

5.2 "Factorisation failed" error

Sometimes the "Factorisation failed: non-positive definite matrix" error is reported immediately at the start of a simulation. This error can be caused by including too few blade elements within each blade part.

This can be resolved by increasing the number of blade elements within each blade part. In the example below, the 3rd blade section is changed from 2 elements to 3.

E.g. Change from : MultiPartSplitStations 1 14 **18 20** 24 32
to : MultiPartSplitStations 1 14 **18 21** 24 32

6 OTHER MULTI-PART INFORMATION

6.1 Multi-part Outputs in $VE File

When a multi-part blade simulation is run in Bladed 4.7, some useful information is output to the simulation $VE file in a section entitled "MULTIPART BLADE MODAL INFORMATION".

Information is output to the $VE file about the coupled modes of the complete blade and about the individual blade part modes.

6.1.1 Coupled mode information

The coupled whole-blade mode frequency, damping and mode shapes are output to the $VE file.

The primary reason that these mode shapes are calculated is to allow specification of damping on familiar whole-blade mode shapes.

A useful check of the validity of the multi-part model of the blade is to ensure that the blade coupled mode frequencies match those calculated for a linear blade model. If this is not the case, then it means that some part of the blade deflection is constrained in a non-physical manner by the multi-part blade definition specified by the user. The solution to this problem is to add more modes on certain blade parts until the coupled mode frequencies match.

A similar check could also be carried out on the coupled mode shapes compared to the linear blade model mode shapes, although this check is more involved.

6.1.2 Individual blade-part mode information

The individual blade-part mode frequency, damping and mode shapes are output to the $VE file. The uncoupled mode damping values calculated by Bladed from the coupled mode damping ratios specified by the user are also displayed in the $VE file.

6.2 Bladed 4.7 Beta Limitations

The following features are not supported in the latest release of Bladed 4.7 at time of writing (4.7.0.88), but are expected to be enabled in a subsequent release of Bladed 4.7.

- Point masses at blade stations

The following features are not supported in Bladed 4.7, but are planned for inclusion in Bladed 4.8

- Pitch bearing not at blade root (also called "split blade").
- Campbell diagram and linearisation calculations.
- The multi-part blade modal analysis is always run as part of the simulation, and cannot be saved before adding multiple simulations to the batch.
- Blade outputs at intermediate points between blade stations.

REFERENCES

1. *Dynamics of Structures*. Clough, Penzien. 2nd Edition 1993.
2. *A time integration algorithm for structural dynamics with improved numerical dissipation: the generalised-alpha method.* Chung, Hulbert. Journal of Applied Mechanics, June 1993
3. *"Improvements to blade geometric stiffness model in Bladed". DNV-GL Technical Note 110052-UKBR-T-32-B.* Available on Bladed User Portal.