Geometric stiffening options in Bladed 4.3 and later

Contents

Author: Will Collier

Doc No: 110052-UKBR-T-22-F

Issue: F

Date of issue: 5 January 2017

Date of latest revision: 12 October 2022

1 OVERVIEW

All Bladed 4.x versions have models for geometric stiffness. Geometric stiffness models are designed to account for the effect of deflection on structural response of flexible components.

There are various models of geometric stiffness available in Bladed, separately including the effect of axial and shear internal forces on blade structural response. The differences between these different modelling options are discussed.

This document recommends and justifies the latest best practice settings for geometric stiffness. In short, the "axial loads only" model is recommended for single-part blade and the "full model with orientation correction" model is recommended for multi-part blade models.

It is also discussed why the default settings for geometric stiffness have been changed in Bladed versions 4.5.0.115, 4.6.0.120 and 4.7.0.93 from the "full" to "axial loads only" model.

Finally, geometric stiffness options in Bladed versions 4.3-4.6 are discussed, as well as tower geometric stiffness settings.

2 WHAT IS GEOMETRIC STIFFENING?

Geometric stiffening models account for changes in structural response due to structural deflection from the reference (undeflected) state. Geometric stiffening models can include contributions from element axial and shear internal forces. These different contributions are discussed in this section.

2.1 Geometric stiffness due to element axial forces

Traditional geometric stiffness models account for the effect of element internal axial forces on structural stiffness. This is illustrated schematically in Figure 2-1. Centrifugal loads in the structural elements lead to a restoring load that tends to increase the stiffness of the blade.

A linear finite element model for an initially straight blade is illustrated on the left side of Figure 2-1. A centrifugal force applied to the blade in its deflected position does not cause a bending moment along the blade. This is normal for linear FE models as deflections are assumed to be small.

On the right side of the diagram, the effect of geometric stiffness is illustrated. As the centrifugal load is applied in the deflected blade position, a bending moment is generated in the blade. This extra bending moment can change the blade flapwise and edgewise frequencies.

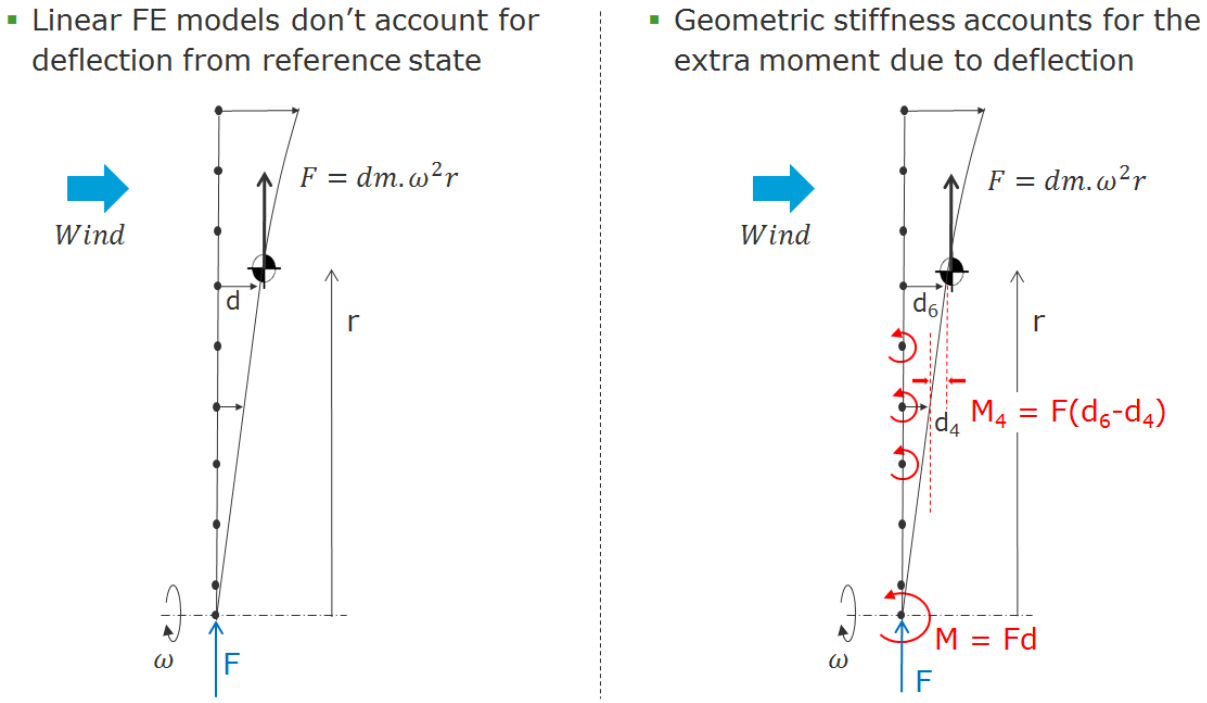

Figure 2-1: Element axial forces causing bending moments in a blade

Geometric stiffness forces in the axial direction are responsible for the well-known "centrifugal stiffening" effect, where blade vibrational frequencies increase with rotor speed. This is illustrated in Figure 2-2.

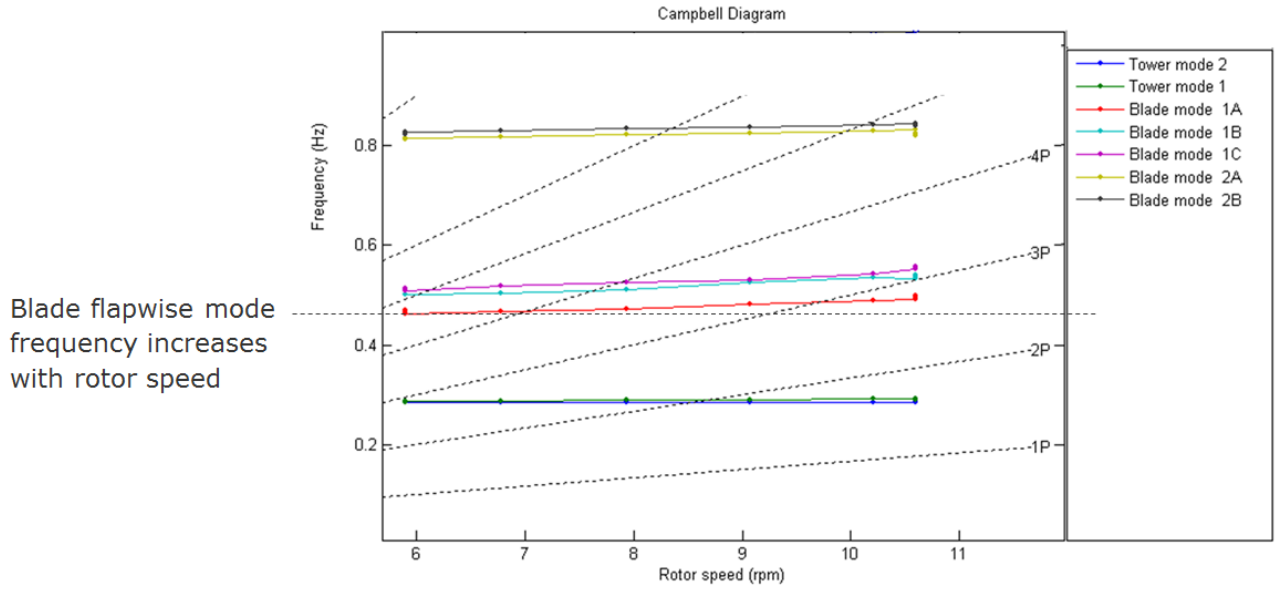

Figure 2-2: Centrifugal stiffening of rotor blades

2.2 Geometric stiffness due to element shear forces

There are also geometric stiffening forces associated with element internal shear forces.

Figure 2-3 illustrates how torsion moments can be generated in the blade by application of shear forces to the blade in its displaced position. On the right side of the diagram, as the drag or lift load is applied in the deflected blade position, a torsional moment is generated in the blade. This extra torsional moment can affect the blade torsional dynamics.

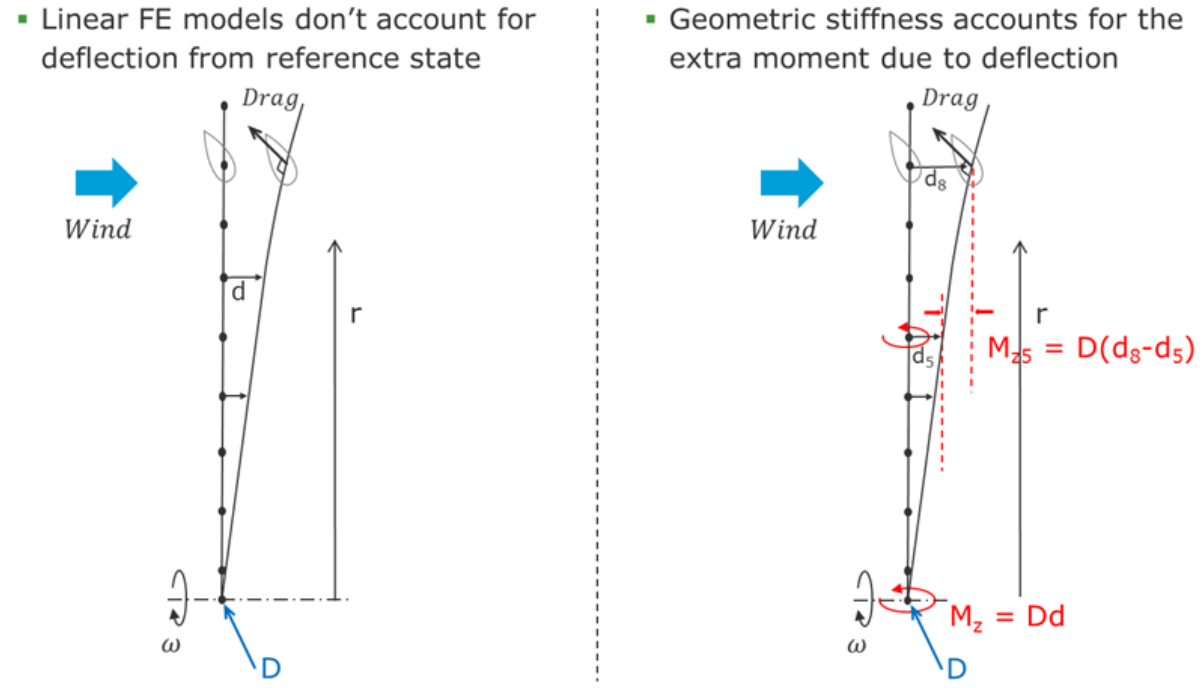

Figure 2-3: Element shear forces causing torsion moments in a blade

When evaluating the geometric stiffness effect of shear forces, it is important to account for the change in orientation of the torsion axis of the blade elements due to deflection. This is illustrated in Figure 2-4, where the difference in internal torsional load between the "reference" and deflected coordinate system is shown.

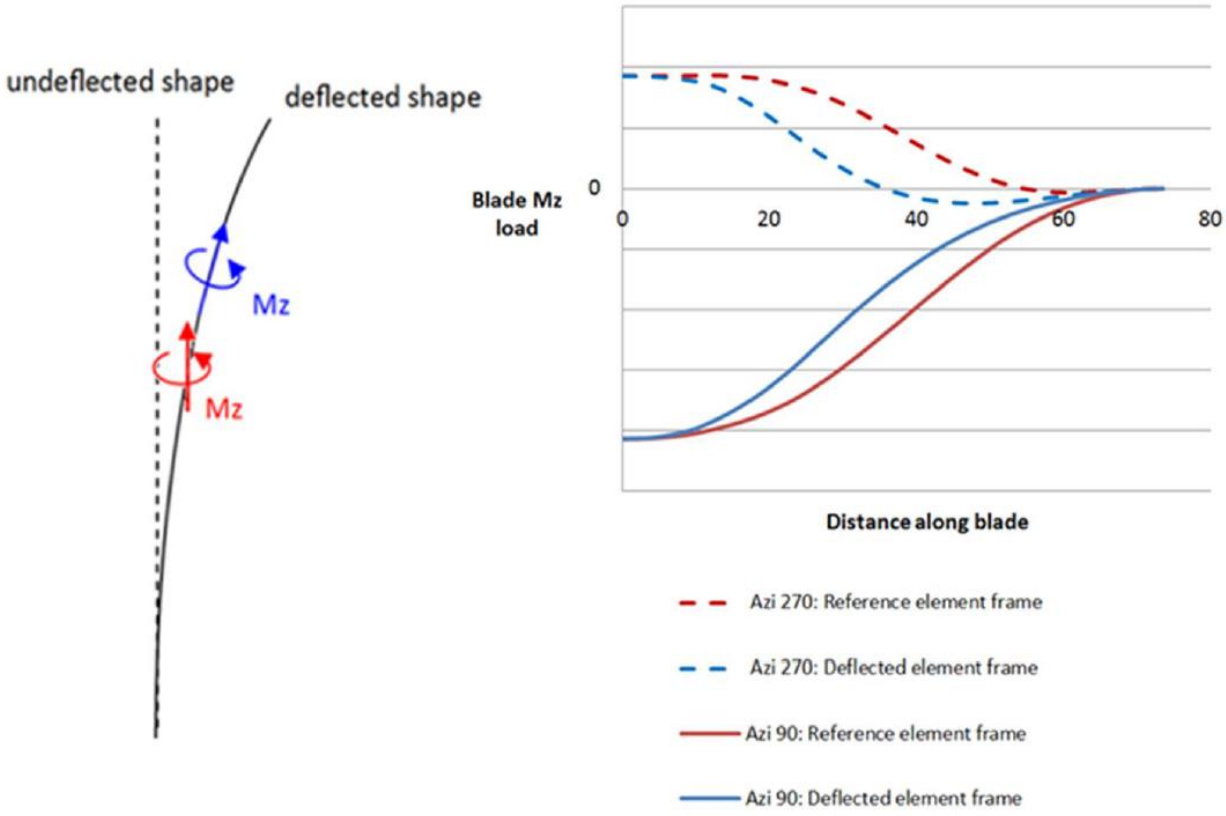

Figure 2-4: torsional blade element load using undeflected and deflected torsion axis orientation

Bladed has models of the effect of geometric stiffness from shear forces both including and excluding the effect of the change in torsion axis orientation due to deflection.

2.3 Geometric stiffness effect in Bladed

Sections 2.1 and 2.2 described how extra loads are generated by displacement of the structure from its reference configuration. The extra loads due to displacements can be accounted for at different points during the Bladed calculation, depending on the level of calculation fidelity required.

Firstly, the geometric stiffness model can account for the effect of modal deflections when calculating the modal accelerations. This is essential to include the effect of geometric stiffness on turbine dynamic response.

Secondly, the geometric stiffness model can alter the deflected shape when calculating the internal member loads. Accurately determining the nodal displacements is a key step in calculating the member internal loads in a statically indeterminate structure.

3 BLADE GEOMETRIC STIFFNESS OPTIONS

This section describes the geometric stiffness options that are available in Bladed version 4.7 and earlier versions, for both multi-part blade and linear blade models.

3.1 Bladed 4.7 geometric stiffness options

There are 6 geometric stiffness options available in Bladed 4.7. Their function and recommended usage is described below.

Note that the default setting for blade geometric stiffness was changed from "full model" to "axial loads only" in Bladed 4.5.0.115, 4.6.0.120 and 4.7.0.93. This was because the "full model" was found to overestimate variation in blade torsion and sometimes cause erroneous blade instability. Blades with significant non-linear deflections should be modelled using a multi-part blade model in Bladed 4.7 or later.

- ✓ **Axial loads only:** Only axial forces are included when calculating the blade accelerations. This is the recommended option for single-part blade simulations. This has always been the default option in Bladed 4.0-4.4. This was made the default option in Bladed 4.5.0.115, 4.6.0.120 and 4.7.0.93.
- ✓ **Full model with orientation correction:** Shear and axial geometric stiffness forces are included, and the change of orientation of the torsion axis due to deflection is taken into account. This is the recommended option for multi-part blade simulations. This model is only available in Bladed 4.7 and later, through Project Info. This model is not the recommended setting for single-part blade simulations as the model is only valid when the deflection within each linear body on the blade remains small.
- ✗ **Full model:** Shear and axial geometric stiffness forces are included, but the change of orientation of the torsion axis due to deflection is **not** taken into account. This model is not recommended for use, although it remains visible in the Bladed 4.7 GUI. This model was the default model in Bladed 4.5-4.7 until versions Bladed 4.5.0.114, 4.6.0.119 and 4.7.0.92.
- ✗ **Tuned full model:** This model is a variation on the "full model" where the contribution of the geometric stiffness forces on the blade torsional mode can be tuned to better match a multi-part blade model. This model is no longer recommended for use, as the performance improvements in multi-part blade make this model obsolete.
- ! **Internal loads only:** Geometric stiffness forces are excluded for the purposes of calculating accelerations, but included for calculation of internal loads. This model is only recommended for testing, and not for load calculation.
- ! **Disabled:** Geometric stiffness forces are excluded for the purposes of calculating accelerations and for calculation of internal loads. This model is only recommended for testing, and not for load calculation.

The differences between the available geometric stiffness options are described in **Table 3-1.**

	Full model with orientation correction	Axial loads only	Full model	Tuned Full Model	Internal loads only	Disabled
Geometric stiffness effect of **axial** forces included when calculating modal accelerations	✓	✓	✓	✓	X	X
Geometric stiffness effect of **shear** forces included when calculating modal accelerations	✓	X	✓	✓	X	X
Change in orientation of torsion axis is taken into account when calculating modal accelerations	✓	X	X	X	NA	NA
Geometric stiffness of axial and shear forces included for internal force calculation	✓	✓	✓	✓	✓	X
When to use?	**Use for multi-part blade models**	**Use for single-part blade models**	**Do not use**	**Do not use**	**For testing only**	**For testing only**

Table 3-1: Geometric stiffening options in Bladed 4.7 and later

In Bladed 4.7, all blade geometric stiffness options except "full model with orientation correction" are available on the blade screen.

The "full model with orientation correction" is only available through Project info by entering the following code

```
MSTART EXTRA
BLADEGEOMSTIFF 5        * Enables the "full model with orientation correction"
MEND
```

3.2 Justification of default geometric stiffness settings

This section briefly discusses the justification for the recommended default values of geometric stiffness for single-part and multi-part blade models.

3.2.1 Single-part blade

For single-part blades the recommended geometric stiffness setting is "axial loads only". Note that the default setting for blade geometric stiffness was changed from "full model" to "axial loads only" in Bladed 4.5.0.115, 4.6.0.120 and 4.7.0.93.

The "full model" of geometric stiffness is no longer recommended for the following reasons

- This model has been shown to over-predict the variation in blade torsion for some flexible blades, leading to erroneous numerical instability.
- For single-part blades, using "axial loads only" rather than the "full model" has been shown to give a better match in loading to a higher fidelity non-linear "multi-part" blade model.

"Axial loads only" is recommended for the following reasons

- Virtually all of the Bladed validation against field measurements has been carried out using this setting, giving a high level of confidence in the model to accurately simulate a wide variety of turbines.
- The model has a proven track record of good numerical stability.
- The geometric stiffness models that include shear forces such as "full model with orientation correction" are only appropriate when angular deflections within each linear finite element body are small (less than say 10°).

3.2.2 Multi-part blade

For multi-part blades the recommended geometric stiffness setting is "full model with orientation correction", for the following reasons

- The deflections in each blade part remain small, so use of geometric stiffness shear terms is appropriate.
- Use of this model instead of "axial loads only" gives convergence of blade load and deflection results with fewer blade parts, allowing improved simulation performance.

3.3 Bladed 4.3-4.6 geometric stiffness options

This section describes the Project Info options that are available for controlling the blade geometric stiffness model in from Bladed 4.3 to 4.6.

Note that the default setting for blade geometric stiffness was changed from "full model" to "axial loads only" in Bladed 4.5.0.115 and 4.6.0.120. The default setting for blade geometric stiffness in Bladed 4.3-4.4 has always been "axial loads only". "Axial loads only" is now the recommended setting for all simulations carried out with Bladed 4.3-4.6. Blades with significant non-linear deflections should be modelled using a multi-part blade model in Bladed 4.7 or later.

The geometric stiffness model is controlled by using the following Project Info code.

```
MSTART EXTRA
BLADEGEOMSTIFF 0                                ! Can take a value 0,1,2,3
MEND
```

From Bladed 4.5.0.111 and 4.6.0.105, it is possible to use the "Tuned Full model" to improve the match of linear blade results to multi-part blade results. However, this model is no longer recommended due to performance improvements in multi-part blade, rendering the "Tuned Full model" obsolete.

```
MSTART EXTRA
BLADEGEOMSTIFF   1                              ! This value must be 1 when using the Tuned Full model.
TORSION_MODE_NUMBER   9                         ! Blade torsional mode number in UI
GEOMSTIFF_MODAL_WEIGHTING_FACTOR    0.5         ! Weighting factor for geometric stiffness on torsional mode
MEND
```

The availability of the five different geometric stiffness options in Bladed versions 4.3-4-6 is summarised in Table 3-2.

	Default geometric stiffness model	Axial loads only	Full model	Tuned Full Model	Internal loads only	Disabled
When to use?		**Use for single-part blade models**	**Do not use**	**Do not use**	**For testing only**	**For testing only**
Bladed 4.6.0.120 and later	Axial loads only	3	Disabled	Project Info above	0	2
Bladed 4.5.0.115 and later	Axial loads only	3	Disabled	Project Info above	0	2
Bladed 4.6.0.105 - 4.6.0.119	Full model	3	1	Project Info above	0	2
Bladed 4.6.0.95 - 4.6.0.104	Full model	3	1	Not available	0	2
Bladed 4.6.0.66 - 4.6.0.94	Full model	Not available	1	Not available	0	2
Bladed 4.6.0.54 - 4.6.0.65	Full model	Not available	1	Not available	0	Not available
Bladed 4.5.0.111 - 4.5.0.114	Full model	3	1	Project Info above	0	2
Bladed 4.5.0.104 - 4.5.0.110	Full model	3	1	Not available	0	2
Bladed 4.5.0.61 - 4.5.0.103	Full model	Not available	1	Not available	0	Not available
Bladed 4.3 and Bladed 4.4	Axial loads only	1	Not available	Not available	Not available	0

Table 3-2: Blade geometric stiffness options in Bladed 4.3 to 4.6

4 TOWER GEOMETRIC STIFFNESS OPTIONS

This section describes the options that are available for controlling the tower geometric stiffness model in from Bladed 4.3 to 4.8.

In Bladed **4.3** and **4.4**, the tower geometric stiffness model is controlled by using the following Project Info code.

```
MSTART EXTRA
TOWERGEOMSTIFF 0      ! Can take a value 0,1  (0 = disabled, 1 = enabled)
MEND
```

Note that in Bladed 4.3 and 4.4, the geometric stiffness model is not valid for statically indeterminate structures (e.g. jacket structures) so should be disabled for such structures. In Bladed 4.3, the tower geometric stiffness model is enabled by default, so should be disabled manually for statically indeterminate structures. In Bladed 4.4 (4.4.0.114 and later), the tower geometric stiffness model is disabled by default for multi-member towers, but enabled by default for towers defined in the monopile screen.

In Bladed **4.5 - 4.7**, the tower geometric stiffness model is controlled via a checkbox on the Bladed tower screen. The geometric stiffness model in Bladed 4.5 and later is valid for statically indeterminate structures.

In Bladed **4.8**, geometric stiffness is controlled on the "Flexibility modeller" screen.

The available tower geometric stiffness options in different Bladed versions are summarised in Table 4-1.

Short name:	Internal loads only	Axial loads only	Full model	Disabled
Geometric stiffness disabled	X	X	X	✓
Geometric stiffness effect of **axial** forces included when calculating modal accelerations	X	✓	✓	X
Geometric stiffness effect of **shear** forces included when calculating modal accelerations	X	X	✓	X
Geometric stiffness of axial and shear forces included for internal force calculation	✓	✓	✓	X
When to use?	Use when tower deflections are small so tower accelerations won't be strongly affected by geometric stiffness.	Use when tower deflections are larger so tower accelerations may be affected by geometric stiffness.	Use when tower deflections are larger so tower accelerations may be affected by geometric stiffness.	Use only for testing and comparison with other software tools
Project Info code **Bladed 4.3 – 4.4**	-	`TOWERGEOMSTIFF 1`	-	`TOWERGEOMSTIFF 0`
Usage in **Bladed 4.5 - 4.7**	Disable check box	-	Enable check box	-
Usage in **Bladed 4.8 and later**	"Flexibility Modeller" screen	"Flexibility Modeller" screen	-	"Flexibility Modeller" screen

Table 4-1: Tower geometric stiffness options in Bladed 4.3 and later