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Non-linear blade model in Bladed for prediction of deflection of large wind turbine blades, and comparison to HAWC2

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Summary

Long and flexible blades for next generation offshore turbines are presenting new aero-elastic modelling challenges. Accurate prediction of blade deflections (particularly torsion) during operation is of particular interest as this can have significant impact on both blade loading and stability.

Traditionally, blade dynamics have been evaluated using linear models of blade deflection, with linear deflection mode shapes calculated and used in aero-elastic simulation codes. Such models are now being pushed beyond their limit of applicability to accurately determine blade loading and evaluate stability. [1] [2] [3]

To address this modelling challenge, non-linear blade structural models are required that more accurately account for the effect of large blade deflections on blade response. To this end, a non-linear blade model has been developed in Bladed v4.7. In this study, blade deflections and loads for the Alstom Haliade 6MW turbine are compared between Bladed and HAWC2, which uses a similar non-linear blade deflection model [4].

Compared to HAWC2, Bladed uses an additional transformation to account for the orientation of shear axis in the blade structure. When this additional transformation is disabled, an excellent agreement is found between the two codes for blade loads and deflections in power production.

Linear and non-linear blade models

Linear models of blade deflection have traditionally been used to analyse wind turbine blade structural dynamics. This approach is illustrated in Figure 1.

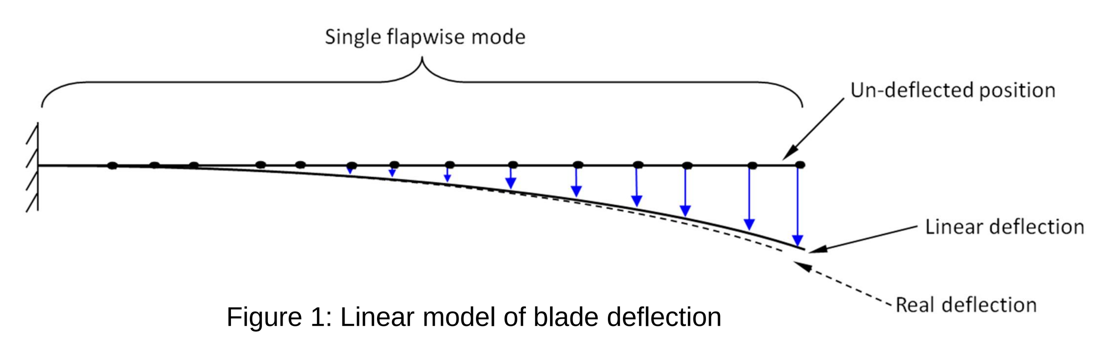

Figure 1: Linear model of blade deflection

Linear models are based on small deflection assumption, so ignore second order effects due to deflection. Such second order effects can be important in determining the torsional loading in a blade and so the blade dynamic response. This effect is illustrated in Figure 2.

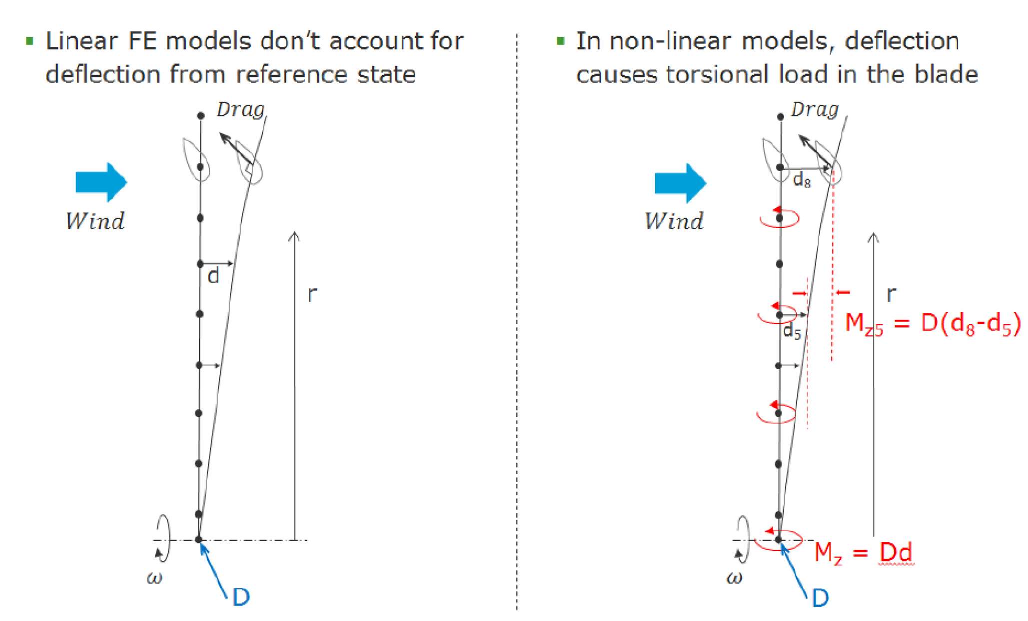

Figure 2: Effect of blade deflection on torsional loading

When deflections are small within a finite element body, such non-linear effects can be accounted for using a "geometric stiffness" model enhancement to a linear finite element model. However, for large flexible blades, a different approach is required that does not rely on small deflections of the whole blade. An accurate non-linear model of deflections can be achieved by dividing the blade structure into several linear parts, as illustrated in Figure 3. Large deflections are modelled accurately as rigid body motion of outer blade parts is included.

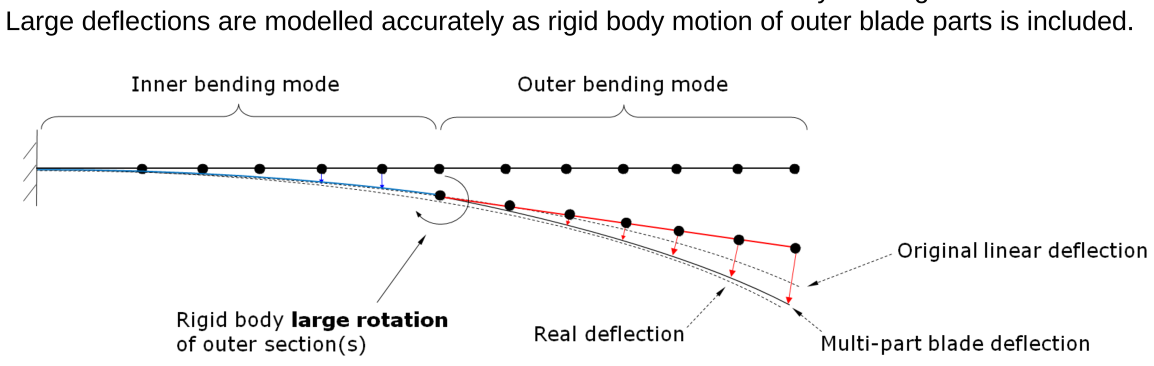

Figure 3: A multi-part blade consisting of 2 parts

Blade loads and displacements for the Alstom Haliade 6MW turbine are compared in Figure 4 for a linear blade model with and without geometric stiffness and multi-part blade (with 9 linear parts). Clearly the linear model blade (with or without geometric stiffness) does not give a good estimate of torsional deflection at the blade tip. Both linear models give larger variation in flapwise bending loads than the multi-part model. The effect of poor torsion prediction in the linear models could be even more profound for extreme load situations.

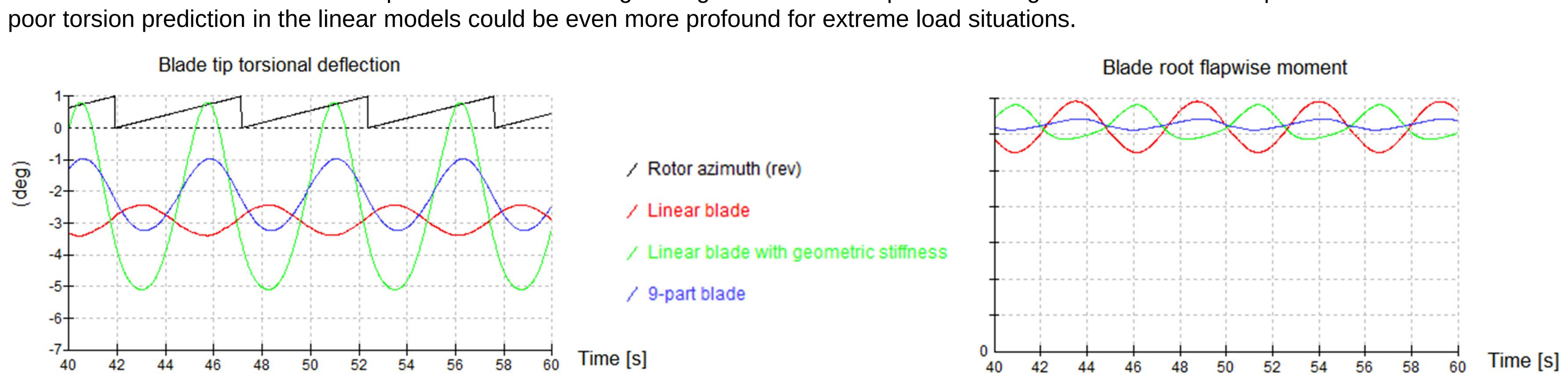

Figure 4: Blade loads and deflections in Bladed with linear and multi-part models

Multi-part blade simulations are more computationally expensive than linear blade simulations, due to a higher number of degrees of freedom with higher natural frequencies. However, through use of an unconditionally stable Newmark Beta integrator in Bladed 4.7, the simulation time increase is moderate, as shown in the table below. In Bladed 4.8, a new matrix library implementation will allow multi-part simulation at approximately the same speed as linear blade simulations.

	Bladed simulation time for 60s simulation in steady wind
Single-part blade	65 s
Multi-part blade (5 parts, Bladed 4.7)	115 s
Multi-part blade (5 parts, Bladed 4.8)	64 s

Modelling of shear axis orientation

Bladed includes a model to account for the orientation difference between shear axis and neutral axis in a blade beam element. The formulation used is very similar to that employed in the ANSYS Beam44 element [5]. As illustrated in Figure 5, the model accounts for both translation and rotational offset between the shear axis and neutral axis.

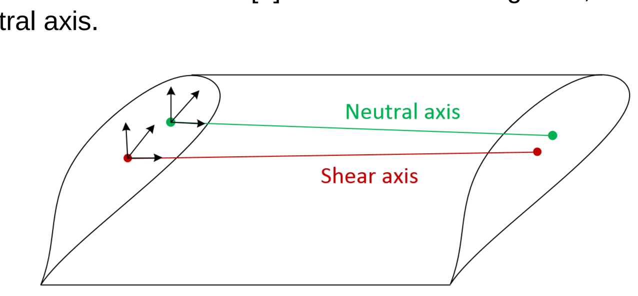

Figure 5: Shear axis translational and orientation offset from neutral axis

The orientation difference between shear and neutral axis results in off-diagonal bend-twist coupling in the element stiffness matrix as shown:

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

In the next section, it is established that these off-diagonal terms in the Bladed element formulation are responsible for most of the difference in blade deflection predictions between Bladed (with multi-part blade) and HAWC2. It is therefore assumed that such a transformation is not used in HAWC2 (i.e. the off-diagonal terms would be omitted in the above equation).

For successful comparison with HAWC2, this feature was disabled in Bladed. In the next section, Bladed results with this model disabled are labelled as "Bladed (no Shear Orientation Correction)" or "Bladed (no SOC)".

Comparison of Bladed and HAWC2

Models were defined in Bladed and HAWC2 of the Alstom Haliade 6MW turbine, which has 73.5m LM blades. In both models, the blade was split into 9 parts in order to give a converged non-linear model of blade deflection. Power production simulations were run in steady wind conditions near rated wind speed, to give large blade deflections. Wind shear was not included.

Blade deflections and blade root loads were reported in the blade root coordinates as shown in Figure 6.

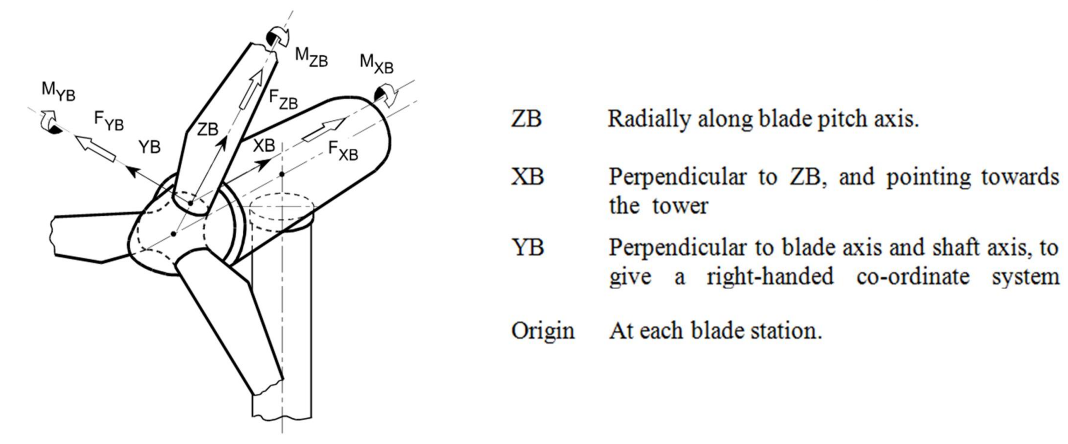

Figure 6: Output coordinate for blade loads and deflections

A comparison of the blade deflection at 70m along the blade is shown in Figure 7. The periodic variation is a result of the changing direction of gravity load with rotor azimuth coupled with applied aerodynamic forces. With the shear orientation correction disabled in Bladed, an excellent agreement is observed between Bladed and HAWC2.

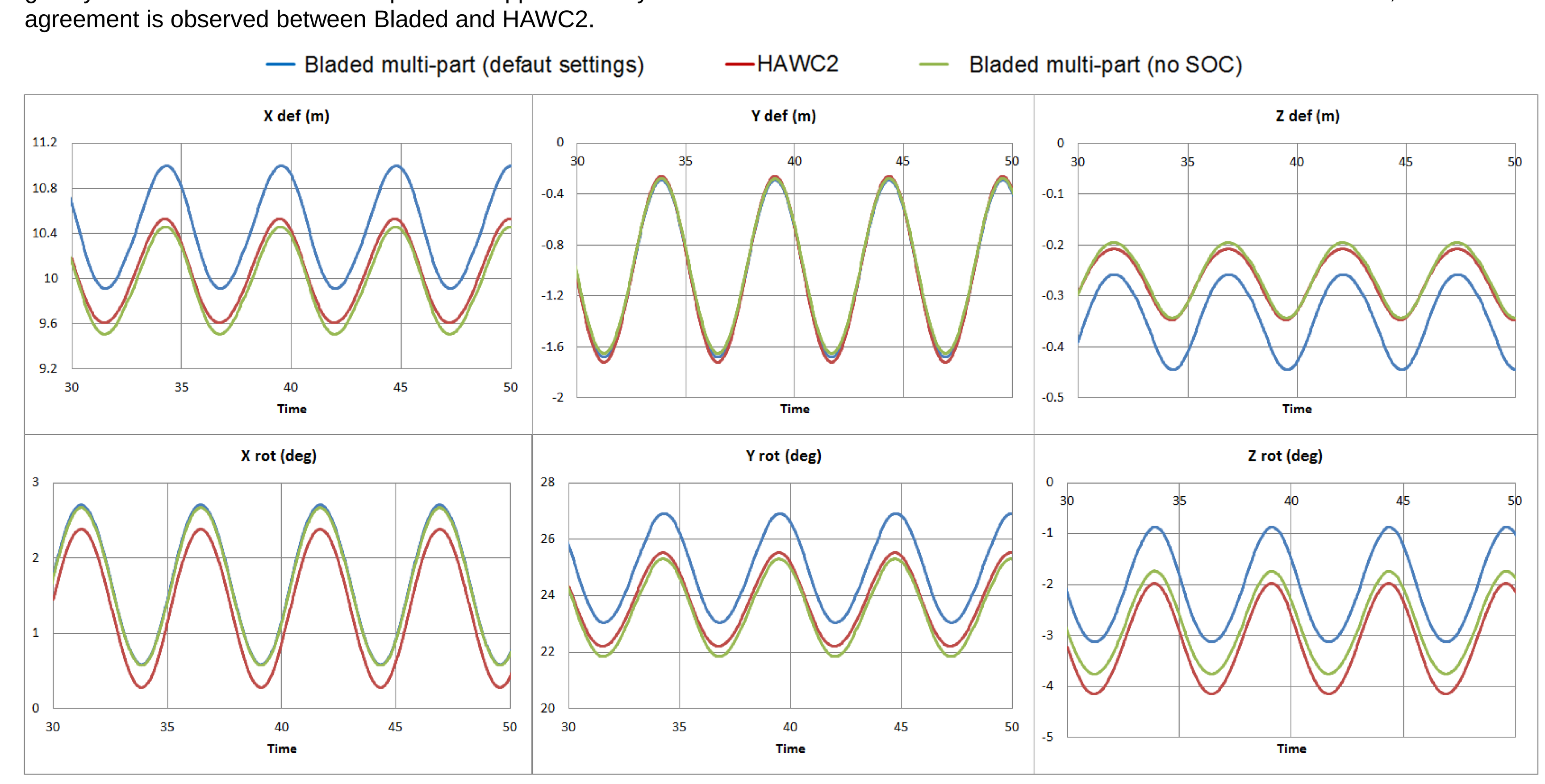

Figure 7: Blade tip deflection (70m along blade) in Bladed and HAWC2

Deflections along the whole blade at time = 31.5s are shown in Figure 8. With the shear orientation correction disabled in Bladed, an excellent agreement is seen in the key variables of X-deflection (flapwise), rotation about Y and rotation about Z (torsion).

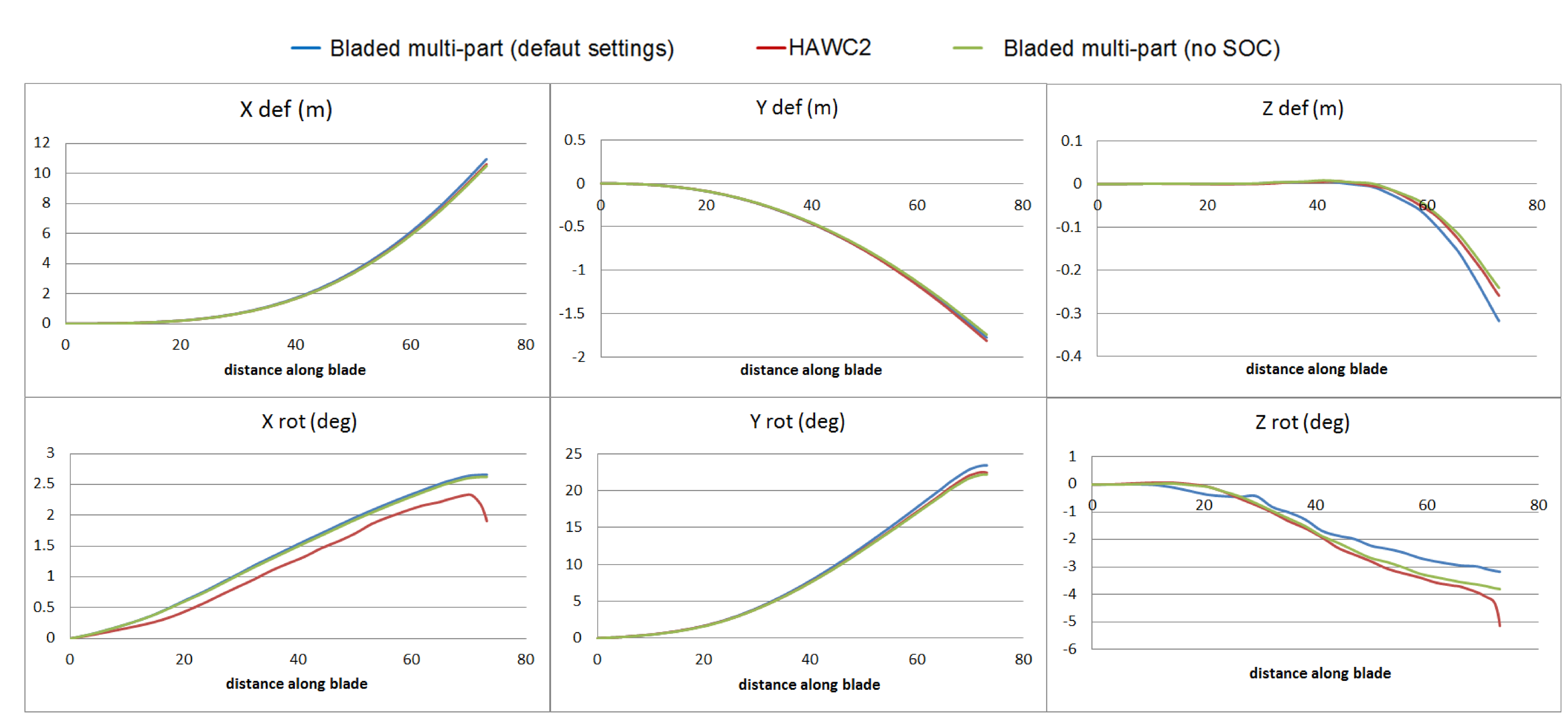

Figure 8: Blade deflections along blade length in Bladed and HAWC2

Finally, bending moments at the blade root are compared in Figure 9. With the shear orientation correction disabled in Bladed, an extremely close match is established between Bladed and HAWC2.

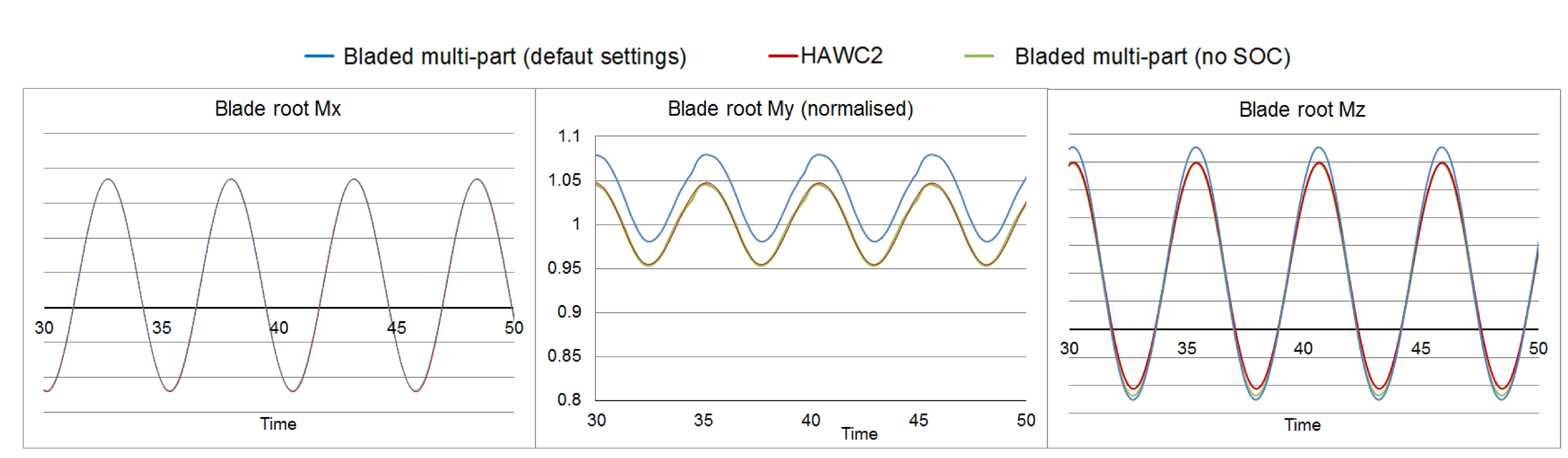

Figure 9: Normalised blade root bending moments in Bladed and HAWC2

Conclusions

A geometrically non-linear multi-part blade model has been implemented in Bladed 4.7, and used to illustrate that linear blade models are not appropriate to predict blade deflection for this 73m blade. The multi-part model is available for design of next-generation turbines in Bladed 4.7.

With the shear orientation correction disabled in Bladed, Bladed and HAWC2 show excellent agreement in terms of blade deflections and loads. With the shear orientation correction included in Bladed, there is some discrepancy between the Bladed and HAWC2 blade deflections, although resulting blade root loads are still very similar.

References and acknowledgements

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