Full non-linear and enhanced linear blade models for prediction of torsion in large wind turbine blades

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1 INTRODUCTION

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

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 torsional response.

2 APPROACH

DNV GL have implemented a non-linear blade deflection model in the widely used aero-elastic code Bladed. Predictions of blade torsional deflections for a 73.5m blade design using this non-linear deflection model are presented and compared to results from the aero-elastic code HAWC2; an excellent agreement is found.

A new method in Bladed to tune an enhanced linear model to match non-linear simulation results is also presented. This offers the advantage of faster simulation time than a full non-linear model, whilst still giving a good estimation of torsional deflection.

3 MAIN BODY OF ABSTRACT

3.1 Linear model limitations

Linear finite element and modal structural models are based on the assumption of small deflections. The stiffness matrix of a body (e.g. a wind turbine blade) is only calculated once in a simulation using the reference (undeflected) structural configuration.

This limitation is illustrated for a straight blade on the left hand side of Figure 3-1. In a linear finite element model, the deflection state is not taken into account when calculating the internal loads that result from application of external loads. On the right hand side of the diagram, torsional loads generated in the blade due to the external load application in the deflected position are illustrated.

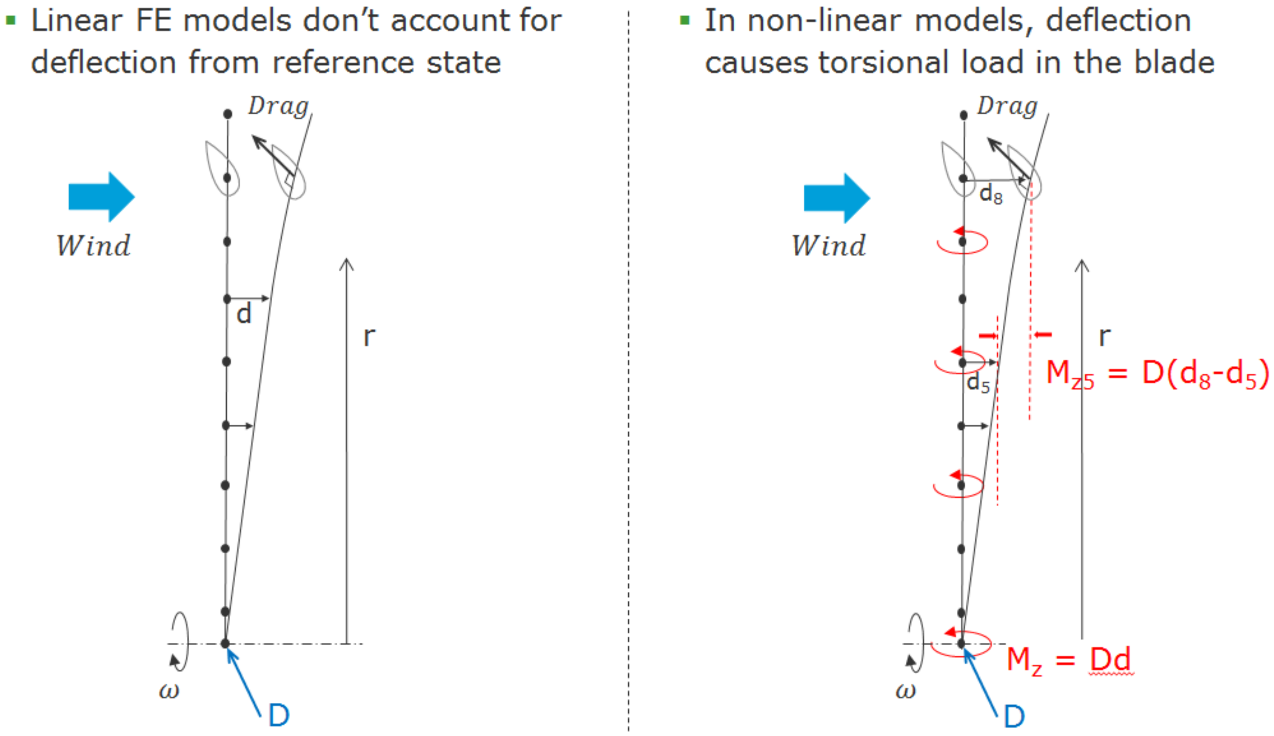

Figure 3-1: Linear and non-linear models of torsion

Due to this effect, it is expected that linear models will not give a good estimate of blade torsion when blade (typically flapwise) deflections are very large.

Figure 3-2 illustrates how the torsion in a blade is expected to vary with rotor azimuth angle, due to the combined application of lift loads and gravity loads. Positive blade torsional deflection is expected at azimuth of 270°, but negative torsion is expected at azimuth 90°.

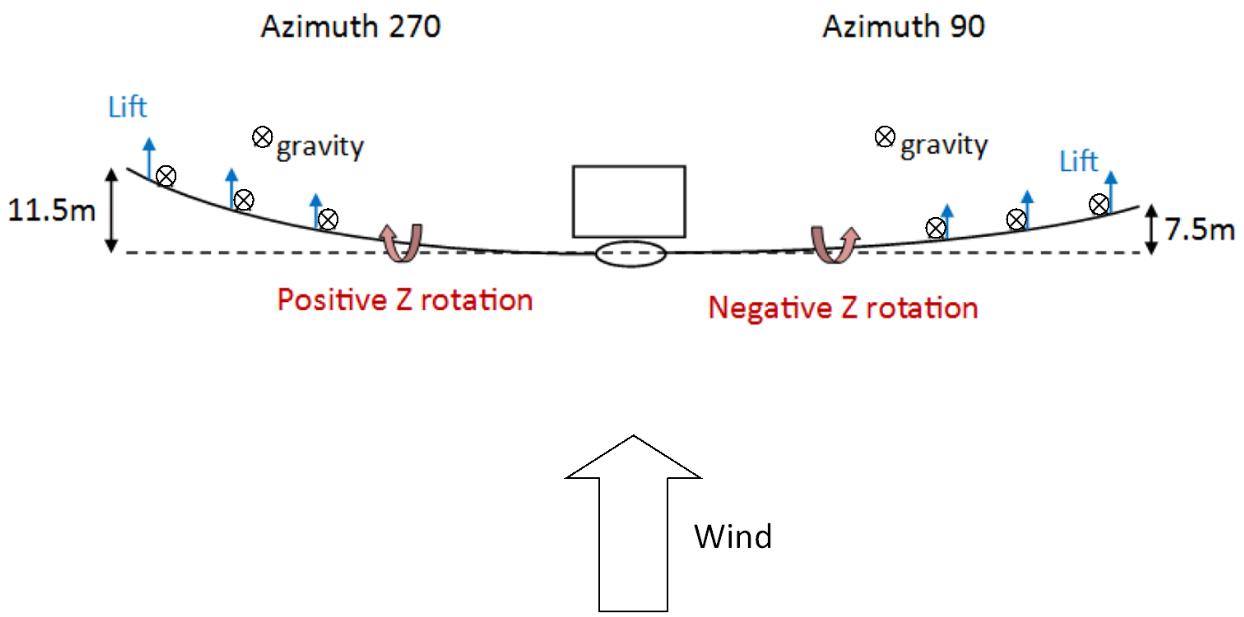

Figure 3-2: Reason for blade torsion variation with azimuth

Simulations were carried out using a linear blade model in Bladed for a particularly flexible commercial 73.5m blade design, where tip deflections of up to 20% of blade length are anticipated.

Figure 3-3 shows the prediction of blade tip torsional deflection using a linear blade model, at 10m/s wind speed. The flapwise tip deflection is approximately 12m in this simulation. There was concern that the prediction of the blade torsion was not very good, due to the linear model assumptions described above.

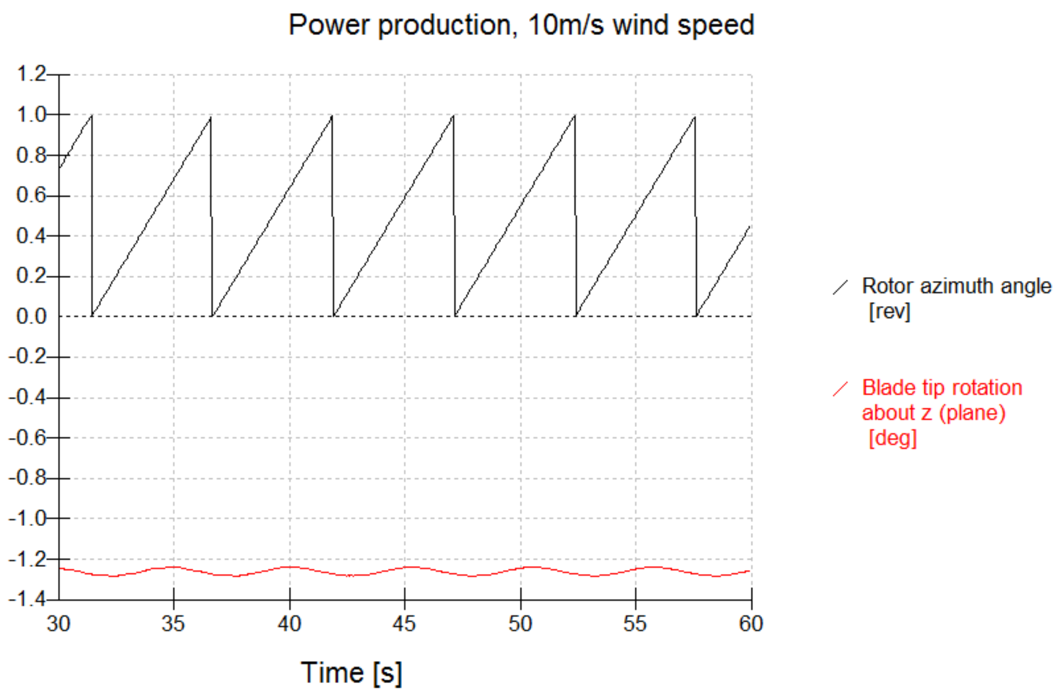

Figure 3-3: Blade tip torsion during power production using a linear blade model

3.2 Non-linear blade model in Bladed

To investigate the effect of non-linearity on the prediction of blade torsional deflection, a non-linear blade model has been implemented in Bladed as part of this research.

A non-linear model has been achieved by splitting the blade into an arbitrary number of linear sections, as illustrated in Figure 3-4. Mode shapes are calculated for each linear blade part. Non-linearity is achieved because outer sections can undergo *large* rigid body rotations as well as small modal deflections within each finite element (FE) body.

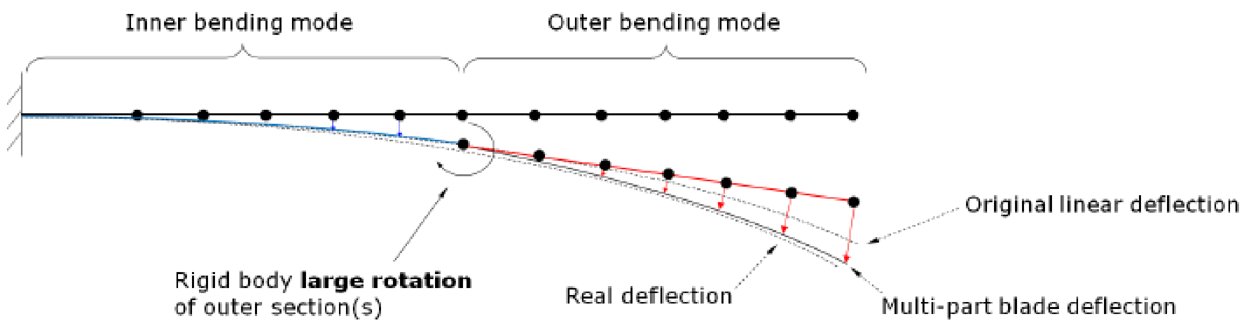

Figure 3-4: Non-linear blade model in Bladed

Figure 3-5 compares the blade tip torsional rotation predictions using the linear and non-linear blade structural models in Bladed. It is observed that the non-linear model predicts increased blade tip torsion compared to the linear model, as expected.

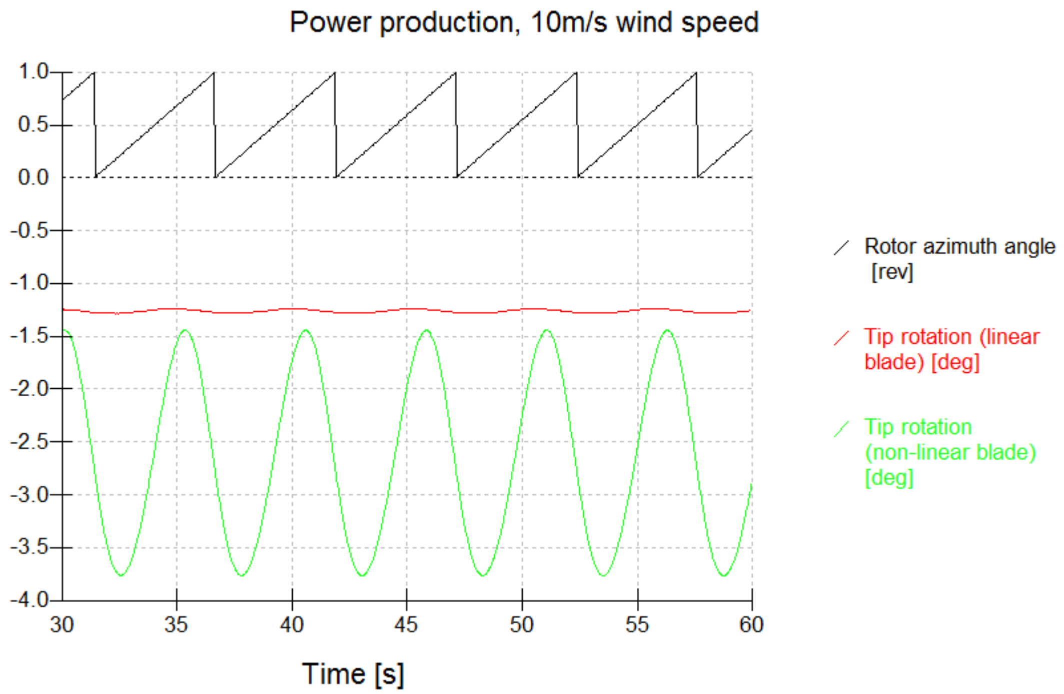

Figure 3-5: Blade tip torsional deflection using linear and non-linear models

To gain more confidence in the blade tip torsional deflection predictions, the results were compared to an equivalent simulation using HAWC2, which also uses a non-linear blade deflection model [1]. Figure 3-6 shows the comparison between Bladed and HAWC2; an excellent agreement is observed.

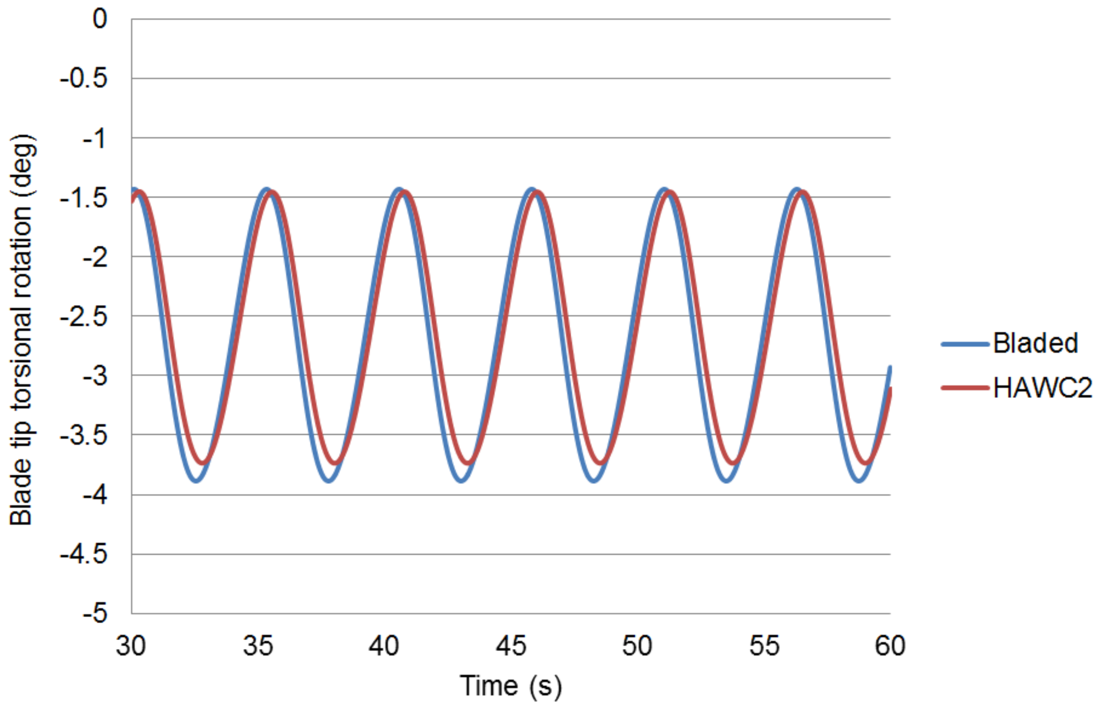

Figure 3-6: Bladed and HAWC2 predictions of blade tip torsion

3.3 Faster simulations with enhanced linear models

The major drawback of non-linear models is long simulation time due to increased simulation fidelity.

An alternative to the full non-linear model is to use a linear blade model, but account for the effect of deflections through a geometric stiffness model. Geometric stiffness models use the deflection state and internal member load to calculate extra applied loads that correspond to applying the load in the deflected position. This method requires iteration but is less computationally intensive than a full non-linear simulation.

A geometric stiffness model as described by Krenk [2] has been implemented in Bladed to add non-linear effects to the linear blade model in Bladed.

In order to give a good match to non-linear results, it was necessary to tune this geometric stiffness model to match the blade tip torsion predicted by the non-linear model. This was achieved by applying a simple constant weighting to the generalised (modal) force that acts on the linear blade torsional mode.

Figure 3-7 shows the prediction of tip torsion using the non-linear blade model, and the “tuned linear model” with the geometric stiffness model effect on the torsional mode weighted as described. It was possible to achieve a good match in blade tip torsional deflection using this simple weighting.

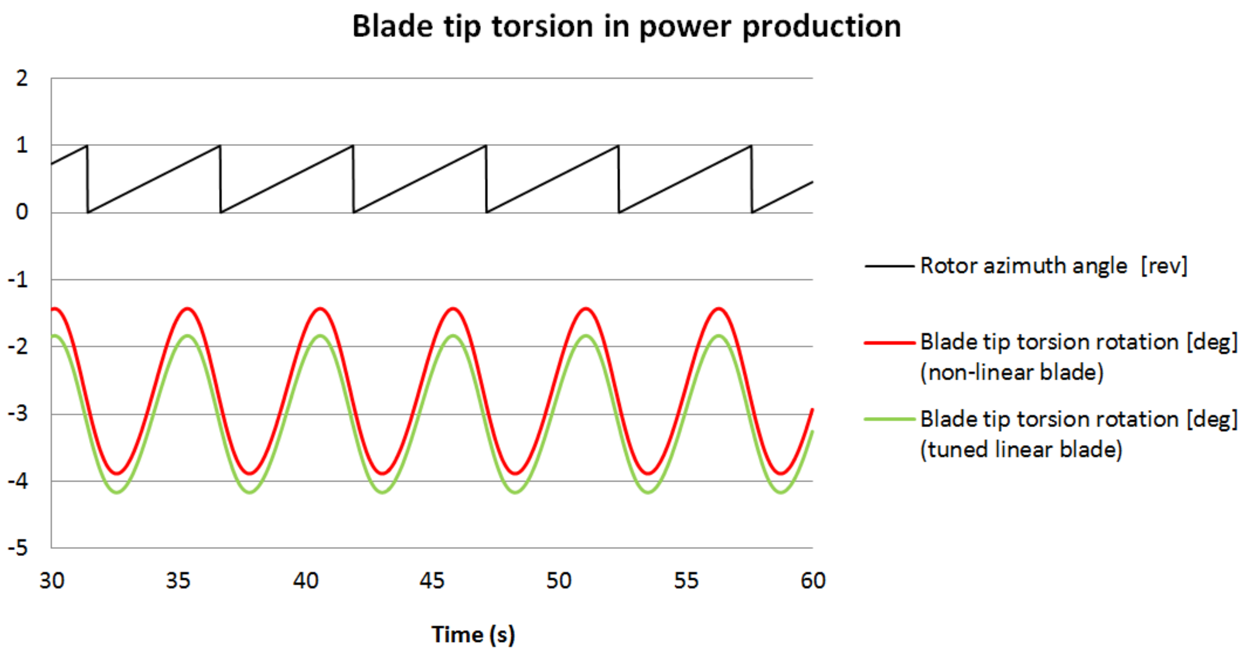

Figure 3-7: Tip rotation using non-linear and tuned enhanced linear model

This tuned linear model also gives good agreement with the non-linear model for the blade flapwise deflection (important for tower clearance analysis) and blade root flapwise loads, as shown in Figure 3-8 and Figure 3-9. The consequences of using a non-linear model for blade design in terms of deflection limit and structural integrity would be quite profound for this blade model.

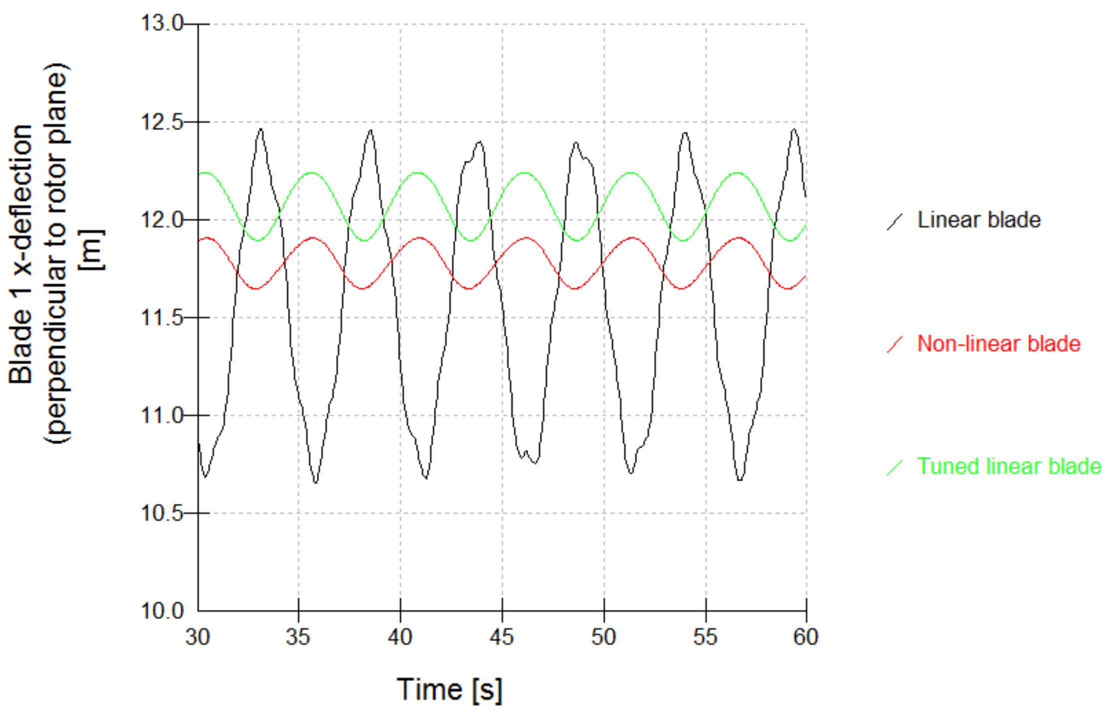

Figure 3-8: Blade flapwise deflection using linear, non-linear and tuned linear models

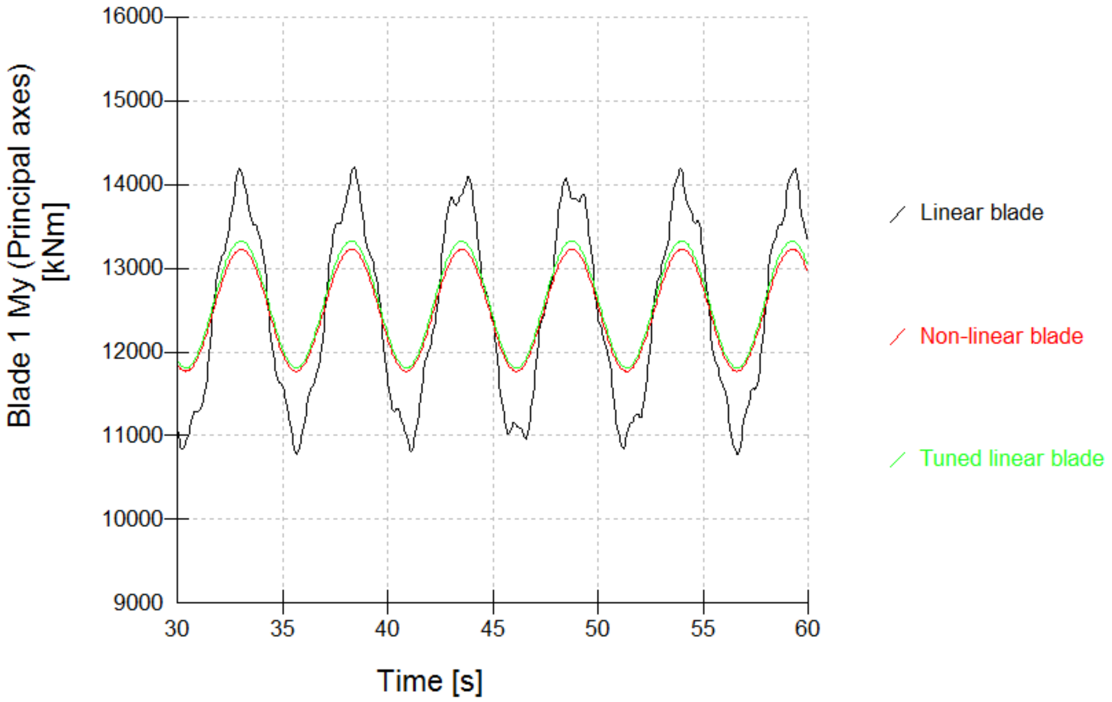

Figure 3-9: Blade root flapwise bending moment using linear, non-linear and tuned linear models

Finally, the simulation times for a 10 minute simulation for the linear, non-linear and tuned linear models are shown in Table 3-1. The number of linear sections for the non-linear blade was increased until convergence was achieved; this required 5 linear blade parts. The tuned linear model is approximately 4 times faster than the 5-part non-linear model, which makes it more practical to use for load calculation purposes where several thousand simulations can be necessary.

Model	**Simulation time (minutes)**
Linear	16
Non-linear (5 linear parts)	180
Tuned linear	40

Table 3-1: Simulation times for linear, non-linear and tuned linear models

4 CONCLUSIONS

A non-linear blade structural model has been implemented in Bladed. Results for blade tip torsion using this non-linear model were compared to HAWC2 and an excellent agreement was found. It was found that a linear blade model does not give a good estimation of blade tip torsional deflection for this blade model.

The ability to tune a geometric stiffness correction to the Bladed linear blade model has also been implemented. It was shown that it is possible to tune this model to give a good match to the non-linear results for blade deflections and loads. The tuned linear model simulation was approximately 4 times faster to run than the non-linear model, making it more suitable for full sets of load calculations.

5 LEARNING OBJECTIVES

1. Upon completion, participants will be understand the benefits of using a non-linear deflection model to predict blade torsion, and the limits of a linear model.

2. Upon completion, participants will understand that an enhanced linear model can give good prediction of blade torsional behaviour, whilst significantly lowering simulation time compared to a full non-linear model.

3. Upon completion, participants will appreciate the importance of demonstrating agreement between the non-linear blade model predictions in Bladed and HAWC2 and the increased confidence this gives to the industry.

REFERENCES

1. HAWC2 Website: www.hawc2.dk/HAWC2-info/Structual-formulation

2. Non-linear modelling and analysis of solids and structures, Krenk S