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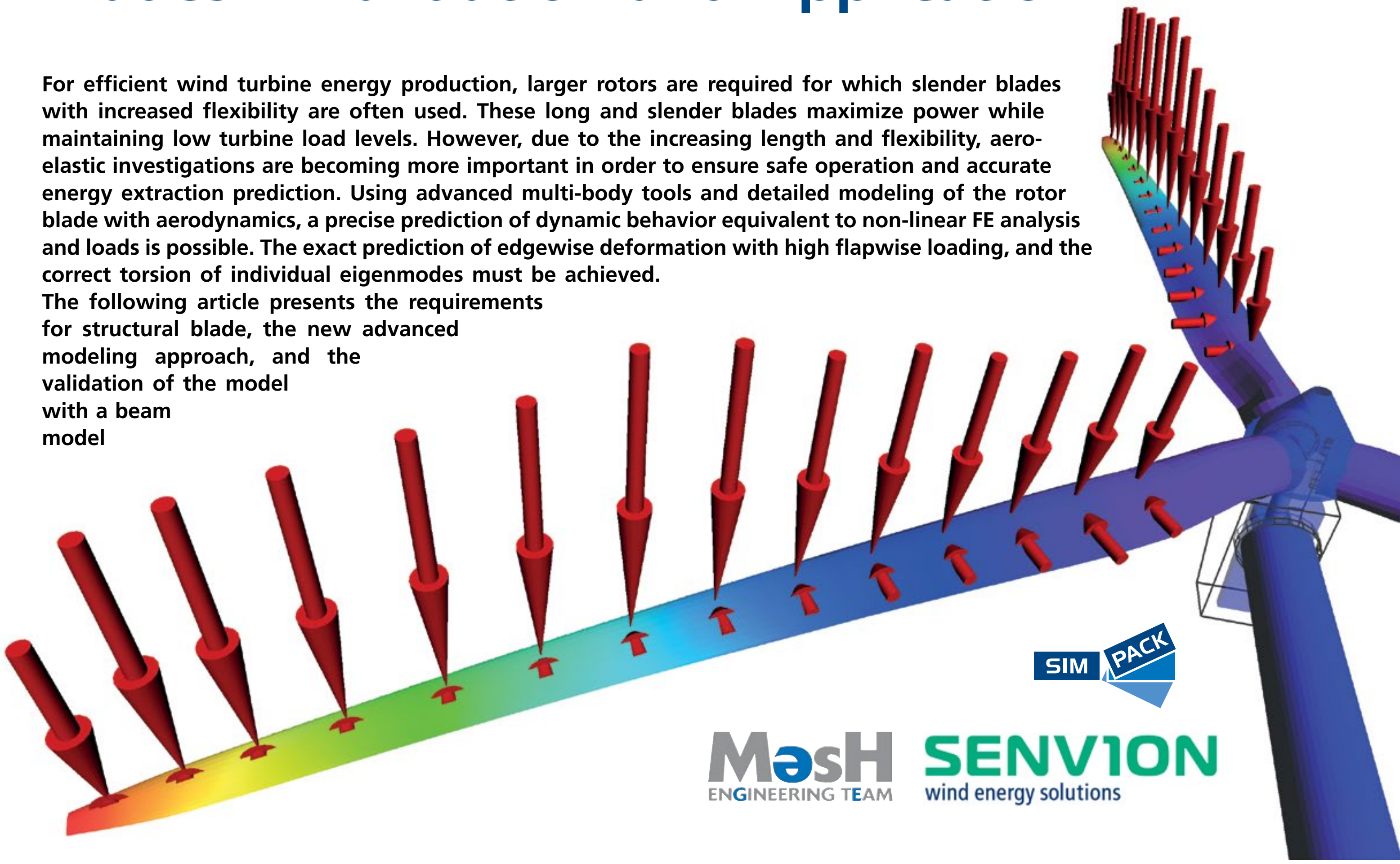
# Advanced Multi-Body Modeling of Rotor Blades — Validation and Application

**For efficient wind turbine energy production, larger rotors are required for which slender blades with increased flexibility are often used. These long and slender blades maximize power while maintaining low turbine load levels. However, due to the increasing length and flexibility, aero-elastic investigations are becoming more important in order to ensure safe operation and accurate energy extraction prediction. Using advanced multi-body tools and detailed modeling of the rotor blade with aerodynamics, a precise prediction of dynamic behavior equivalent to non-linear FE analysis and loads is possible. The exact prediction of edgewise deformation with high flapwise loading, and the correct torsion of individual eigenmodes must be achieved. The following article presents the requirements for structural blade, the new advanced modeling approach, and the validation of the model with a beam model set in the FE code ABAQUS. Data from the UpWind 61.5 m blade was used. Additionally, impact on aeroelastic performances simulations with the complete rotor were carried out, and a comparison between traditional modeling approaches and the new advanced method is offered.**



## REQUIREMENTS FOR STRUCTURAL BLADE MODELING

Aerodynamic lift and drag are the fundamental forces for efficient rotor design. These forces are responsible for the power yield generated by the turbine, and it is therefore essential to maximize the lift-to-drag ratio using an appropriate design.
The coefficient for the lift depends on the angle of attack. As the angle of attack increases, the air is deflected through a larger angle, and the vertical component of the airstream velocity increases resulting in more lift. The lift reaches a maximum at a certain angle. Increasing the angle of attack beyond this critical angle of attack causes the air to become turbulent and separate from the wing; there is less deflection downward, and less lift is generated (Fig. 1) whilst the drag increases significantly. This phenomenon is known as stall.
In order to increase power extraction, maximum aerodynamic lift forces need to be reached and stall effect avoided. This requires precise computation of the torsion of the rotor blade.

*"This requires precise computation of the torsion of the rotor blade."*

## MODELING APPROACH

For modeling the structure of the rotor blade in the multi-body system's wind turbine, flexible bodies are used. A model of 3D beam structure is set up using parameters which describe the geometry, stiffness, and properties. The advanced blade also considers shear and elastic centers, and center of gravity (Fig. 2), and generates a

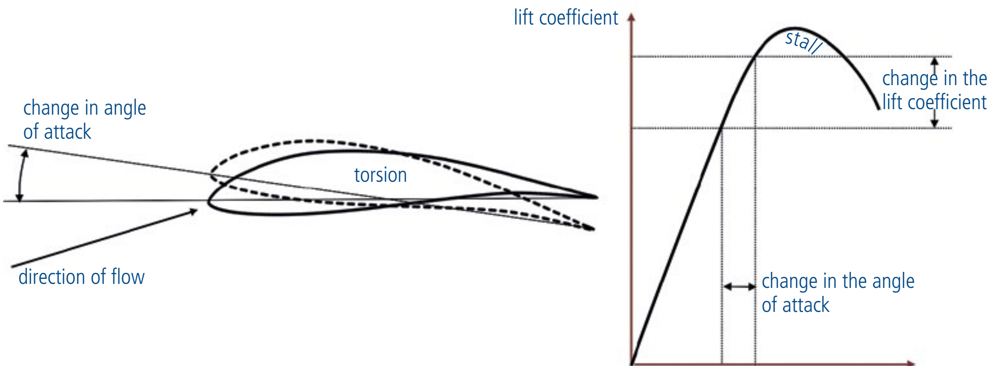



*Fig 1: Influence of the angle of attack on the lift forces*

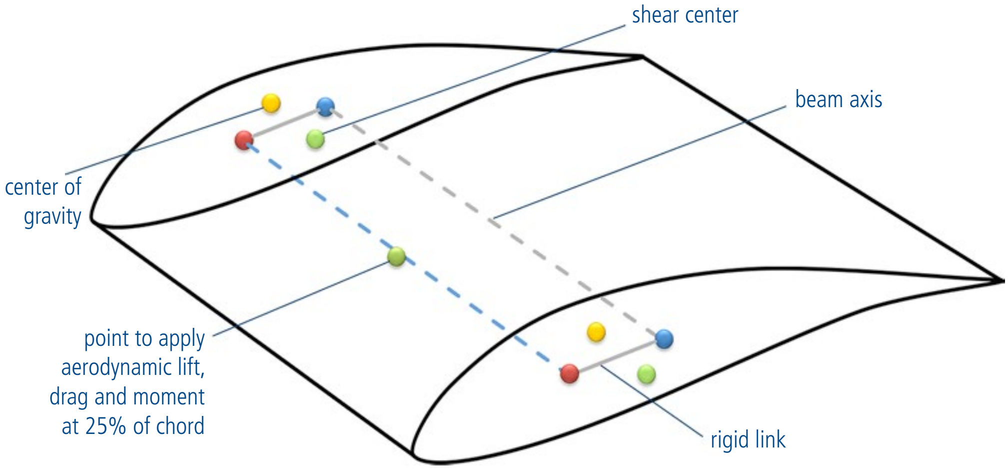



*Fig 2: Advanced 3D beam structure*

more sophisticated modal representation considering the coupled bending torsional deformations. The rotor blade is generated based on all parameters mentioned above using the SIMPACK Rotorblade Generator. The generated rotor blade model can be used as a substructure in an entire wind turbine model.

The flexibility of the beam structure is represented by beam elements using the classical Timoshenko beam theory. Mass and stiffness matrices of the linearized model are used to generate the modes, which are required for the modal representation in SIMPACK. This modal approach is suitable for representing the deformation in the case of small loads and deflections, respectively. The linear SIMPACK result matches the linear ABAQUS result (Fig. 4). The discrepancy between the non-linear ABAQUS results and the linear ABAQUS results in Fig. 4 shows the significant influence of non-linear effects due to the high deflection of the rotor blade during turbine operation. These must be accounted for in SIMPACK by considering second order terms in the modal approach. These 2nd order terms are obtained from geometric stiffness matrices, which consider the non-linear, longitudinal shortening component of the beam structure, the influence of centrifugal forces on the stiffness, and further effects. Additionally, the non-linear kinematic representation of the joints contributes to the geometric non-linear description if the rotor blade is split into individual bodies. In this approach, the individual bodies are rigidly connected by zero degrees of freedom joints. As joints are always kinematically non-linear, the large deformation of the split rotor blade can be computed more precisely. This approach is similar to the FEM warped stiffness approach; see [2]. The benchmark computations revealed that both methods, second order terms and subdividing, need to be considered in order to predict bending-torsion coupling with sufficient accuracy, see Fig. 4.

## VALIDATION RESULTS

Validation of the blade model is based on two load cases. The first load case, representing maximal loading near rated power, consists of distributed lift forces which result in the maximum deflection of the blade encountered during operation (Fig. 3). In order to compare models with different torsional behavior, the applied forces do not rotate with the deformation and remain fixed during the simulation. The aim of this load case is to validate the stiffness of the model in flapwise, edgewise and torsional direction as well as the coupling between these degrees of freedom.

Fig. 4 shows the torsional deflection for the first load case for the aforementioned models. The linear SIMPACK model shows a maximum difference of about 40 % for the torsion angle compared to the ABAQUS non-linear solution. This can have a significant effect on the aeroelastic behavior. The deviation of the SIMPACK model considering the geometric non-linear effects and the 2nd order modal approach to the ABAQUS non-linear solution is less than 4 %. Deformation near rated power shows an acceptable accuracy if the geometric non-linear effects are considered by subdividing the body into 15 sections and by considering a 2nd order modal approach in SIMPACK.

The second load case represents the rated power and consists of the distributed lift forces of the first load case (Fig. 3) and, additionally, the centrifugal forces at rated speed. This load case focuses on additional analyses of eigenfrequencies and mode shapes under loaded conditions to ensure correct dynamic response behavior of the model due to excitations in the deformed state. For example, the coupling of edgewise deformation and torsion in the first

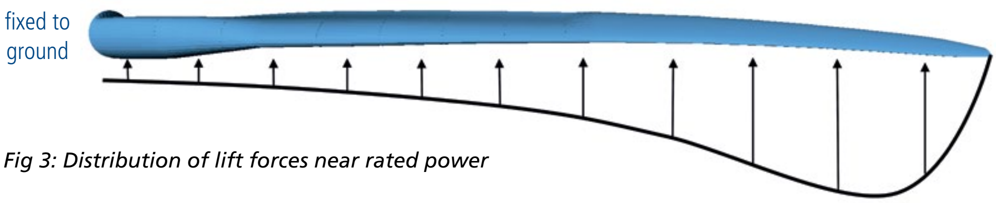



*Fig 3: Distribution of lift forces near rated power*

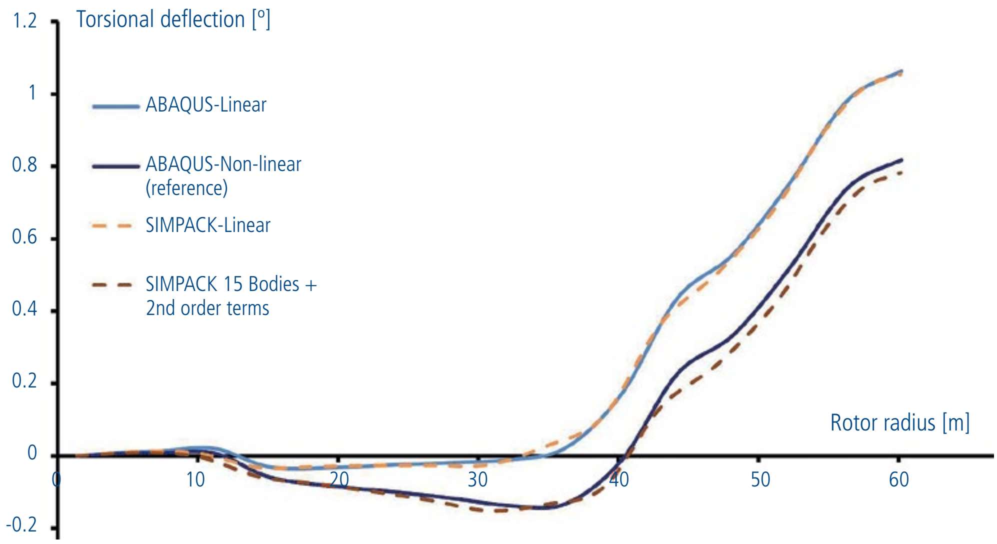



*Fig 4: Torsional deflection due to distributed lift forces near rated power*

edgewise mode enables comprehensive understanding of the changing torsion during each revolution of the rotor.

For all modes up to the second torsional mode, about 10 Hz, the eigenmode deviations of the SIMPACK model, considering the geometric non-linear effects by subdividing the body into 15 sections and by considering a 2nd order modal approach in SIMPACK, are in the range of 2 %.

Fig. 5 shows the normalized nodal deformation of the three rotational degrees of freedom of the 3rd flapwise mode in a loaded state. This bending mode also includes a significant torsional component, which can be accurately modeled by using splitting and considering the second order terms in the modal approach.

## IMPACT ON AEROELASTIC PERFORMANCE

Since validation of the advanced modeling approach has been achieved, the impact of this model on the design process has to be evaluated. Aeroelastic simulations are performed considering the linear rotor blade model as well as the model generated by applying the new advanced approach. Both models are connected to a multi-body model of the entire wind turbine structure which is loaded by external forces, i.e., the aerodynamic forces and the air-gap torque of the generator (Fig. 6). The wind turbine controller model has been coupled to the multi-body model using a standard interface. The details of this modeling approach have already been published in [3]. The UpWind turbine is used to simulate a selection of load cases with the two different modeling approaches for the rotor blades, the linear blade model and the advanced blade model that is split into 15 bodies. In the linear rotor blade approach, only the rotor blade bending in flapwise and edgewise direction is considered with four bending modes in total. Torsional and tensile stiffness values are assumed to be infinite. The bending moments have no impact on the torsional deflection of the blade. This approach represents the traditional method for aeroelastic simulation, which is realized in aeroelastic simulation codes such as Flex5 or FAST [4].

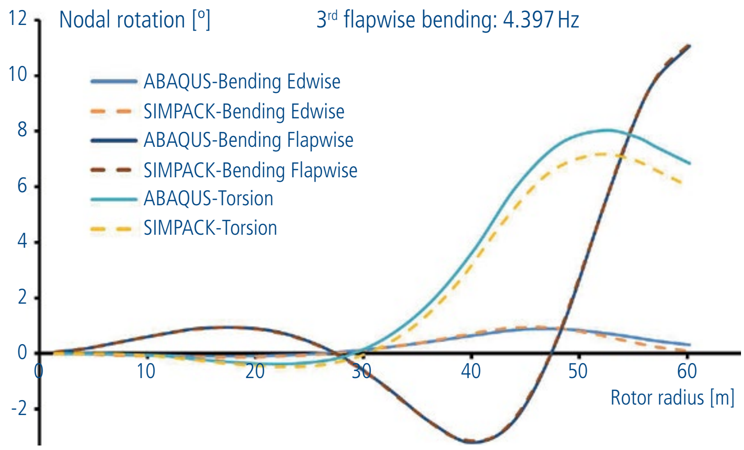



*Fig 5: Normalized nodal rotation for the 3rd flapwise bending mode*

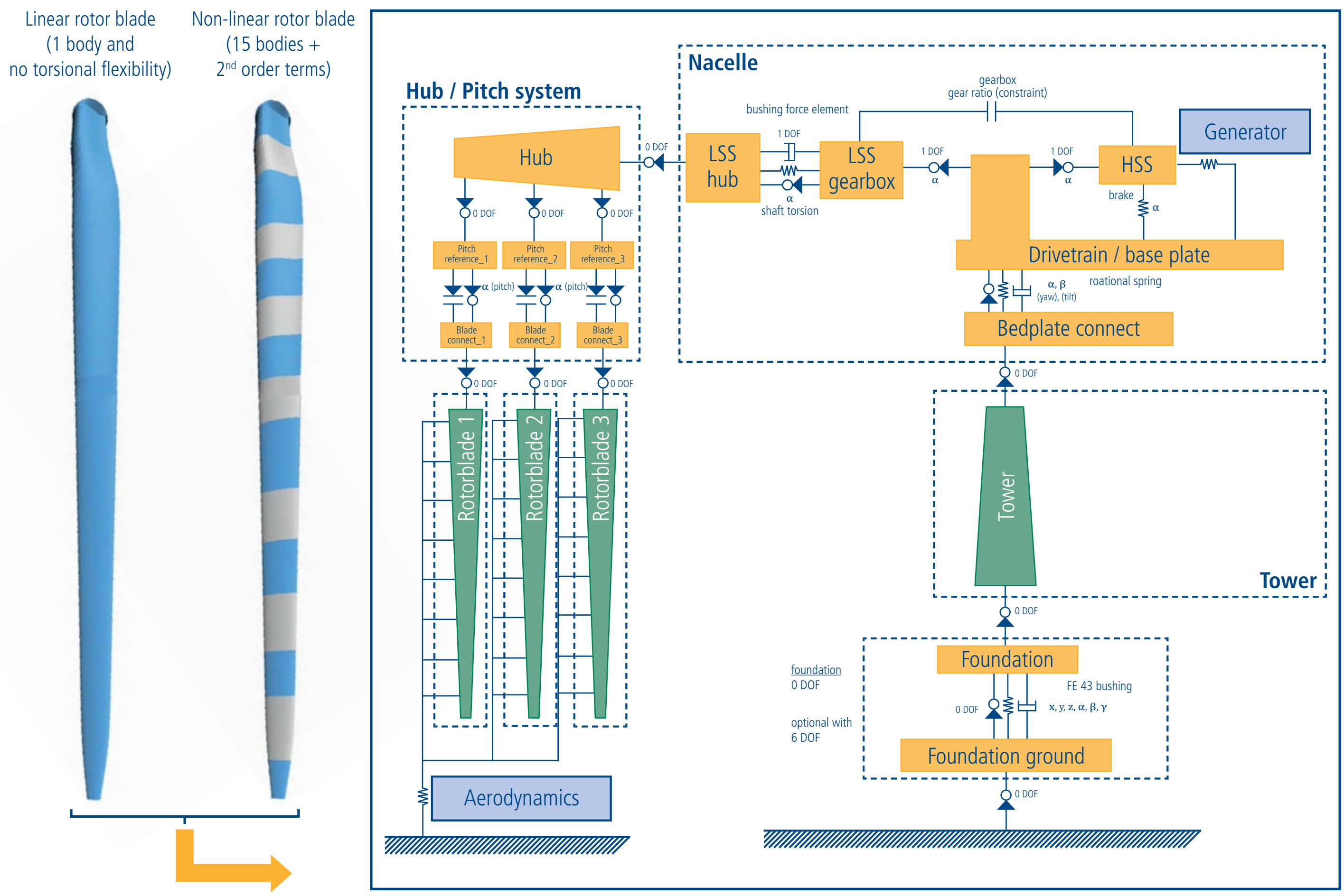



*Fig. 6: Wind turbine model considering the linear and non-linear rotor blade model*

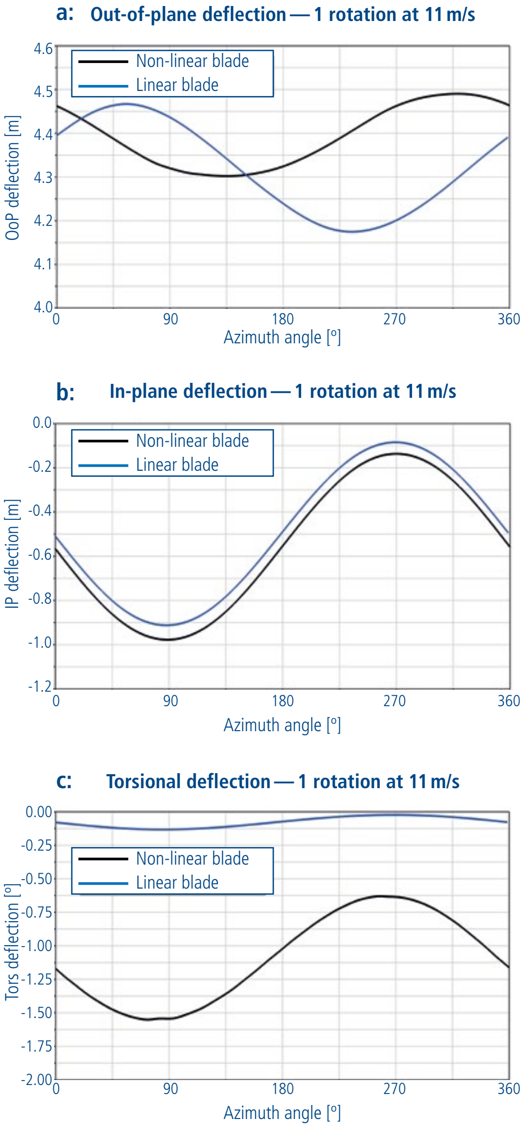



*Fig. 7: Tip deflection over azimuth angle, 0° = pointing upwards: out-of-plane deflection (a), in-plane deflection (b), and torsional deflection (c)*

The rotor of the UpWind turbine is simulated in the time domain at conditions with maximum deflection near rated power. The rotor cone and tilt angle are set to zero to eliminate any misleading aerodynamic effects, e.g., explained in [5], that interfere with the aeroelastic effects that are under investigation. The wind turbine is loaded by a homogeneous wind speed of 11 m/s, close to the rated wind speed of this turbine (11.4 m/s). The pitch controller is not active in partial load so the pitch angle remains constant. The resulting tip deformation of one rotor blade over the azimuthal blade position, as calculated with the individual rotor blade models, is shown in Fig. 7. A rotor blade with the azimuth angle of 0° is pointing upwards.

The out-of-plane deflection shown in Fig. 7a differs with the used rotor blade model. Validation has shown that the out-of-plane deflection due to a constant lift force is predicted similarly in cases of both the linear and the non-linear rotor blade model. This means that the out-of-plane deflection, as shown in Fig. 7a, results from different aerodynamic forces. Opposing the out-of-plane deflection, the in-plane deflection is more similar as predicted by the different rotor blade models (Fig. 7b). This can be explained because the in-plane loads are dominated by the gravitational forces which are similar for the different rotor blade models. The small offset can be assigned to the difference in aeroelastic loading as explained as follows.

To understand the differences in aeroelastic loading depending on the blade model, it is useful to focus on the torsional deflection of the rotor blade over the azimuth angle as shown in Fig. 7c. The linear model is not capable of representing the torsional deflection at all. The small torsional deflection that can be observed is not significant and can be ascribed to fundamental modeling assumptions. As shown in Fig. 4, a torsional deformation comes along with a static flapwise deflection, which is accurately represented in the case of the non-linear model. Since Fig. 7a shows a significant mean flapwise deflection, the resulting mean value of torsional deflection can be explained for the non-linear model. The torsional variation over the azimuth angle can be explained with the coupling of edgewise deformation and torsional deflection. The contribution of the torsional deformation is predicted with the non-linear model. This leads to the variation of the torsional deflection in the same phase as the edgewise deformation with the non-linear model. This effect is not included with the traditional modeling approach.

***"The torsional variation over the azimuth angle can be explained with the coupling of edgewise deformation and torsional deflection."***

Fig. 8 illustrates the blade tip out-of-plane velocity of one rotor blade. The dependency of the aeroelastic loading on the blade deflection can be explained with the additional use of Fig. 9. In the case of the linear blade model, the variations in the angle of

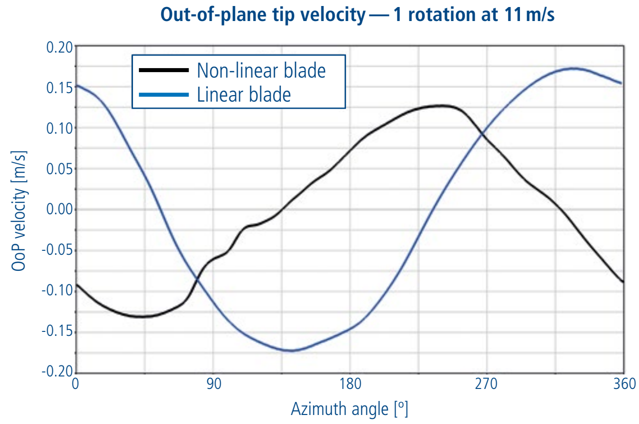



*Fig. 8: Out-of-plane tip velocity over azimuth angle, 0° = pointing upwards*

| | Blade model | Deflection | | Blade model | Deflection |
|---|---|---|---|---|---|
| Out-of-plane deflection B1 | Linear | 8.46 m | Tower base moment side-side | Linear | 21942 kNm |
| | Non-linear | 8.10 m | | Non-linear | 19318 kNm |
| | **Difference** | **-4.3** % | | **Difference** | **-12.0** % |
| Out-of-plane deflection B2 | Linear | 7.18 m | Tower base moment fore-aft | Linear | 91942 kNm |
| | Non-linear | 7.00 m | | Non-linear | 88737 kNm |
| | **Difference** | **-2.6** % | | **Difference** | **-3.5** % |
| Out-of-plane deflection B3 | Linear | 7.35 m | Tower base torsion | Linear | 8429 kNm |
| | Non-linear | 7.10 m | | Non-linear | 5987 kNm |
| | **Difference** | **-3.4** % | | **Difference** | **-29.0** % |

*Table 1: Loads and blade deflections calculated with the linear and the non-linear blade model*

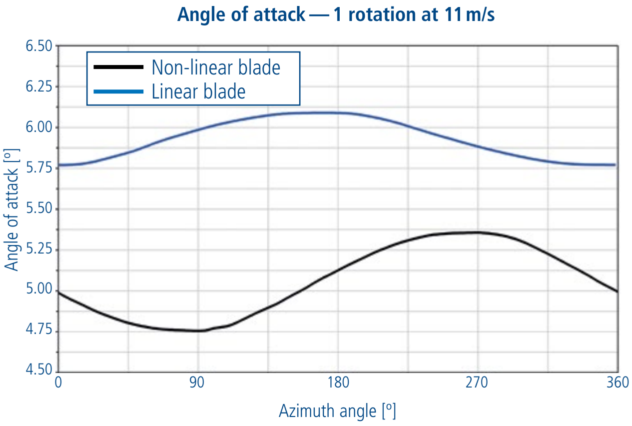



*Fig. 9: Angle of attack over azimuth angle, 0° = pointing upwards*

attack are caused by the out-of-plane blade velocity. A rotor blade deflecting in wind direction, shown positive in Fig. 8, lowers the angle of attack; a rotor blade deflecting into the wind with a negative structural velocity causes a higher angle of attack. This correlation can be seen in Fig. 8 and Fig. 9 since the phases of the angle of attack and the out-of-plane tip deflection are in opposition for the basic blade. In the case of the non-linear blade, this correlation cannot be seen. Instead, the coupling of the angle-of-attack to the rotor blade torsion, as shown in Fig. 7 c, is dominant. Due to the variation in angle of attack, the aerodynamic lift force varies, as the angle is below the stall region. The resulting varying lift force then causes a varying rotor blade tip deflection as shown in Fig. 7 a and Fig. 7 c.

***"This new method enables accurate prediction of aeroelastic loading and rotor blade dynamics for all operating points."***

## POWER CURVE

To evaluate the benefits of the advanced non-linear blade modeling approach, Fig. 10 illustrates the power curve as predicted using the linear and the non-linear rotor blade including the deviation of both curves and the torsional tip deflection as predicted using the advanced non-linear method. The deviation at the cut-in wind speed of 3 m/s is about 12.5 %. The power as predicted using the non-linear model is higher than the power predicted using the linear basic model. This is explained by the wind turbine rotor that is not in its optimal rotational speed at cut-in because of the limited rpm range. The rotor velocity is above its optimum velocity resulting in a high axial induction. The negative torsional tip deflection reduces the angle of attack, resulting in a lower axial induction, which is closer to the optimum. For a higher wind speed of more than 7.5 m/s, the effect of the torsional deflection is inverted. The rotor is at its optimum rotational speed with the negative torsional deflection lowering the angle of attack, leading to a lower power output. The effect of the torsional deflection to the power curve is only visible for the turbine operating in partial load conditions since at rated conditions, the wind turbine controller keeps the power constant. It can be concluded that the effect of blade torsion should be included in the power curve calculation if a high reliability is required.

## RELEVANCE IN A DESIGN LOAD CASE — IEC DLC 1.4

To evaluate the relevance of increased accuracy for the design process, a DLC as defined by IEC that is sensitive to the structural blade modeling, is evaluated with both modeling approaches. In the IEC DLC 1.4, an extreme coherent gust, which occurs with a simultaneous change of wind direction, has to be simulated while the turbine is in power production mode. The quality of the advanced non-linear blade design becomes relevant especially for rapid change of the aerodynamic load level. Table 1 shows the out-of-plane deflection for the three rotor blades. The maximum deflection values, as predicted with the advanced non-linear model, are generally smaller compared to the linear model. The difference of up to 5 % shows that the results derived with the linear model are conservative, but there is some optimization potential that can be exploited using the advanced non-linear model. Table 1 also displays the overturning moments for the tower base. The tower base loads differ between the determined blade modeling approaches. It can be concluded that all of these predicted moments are significantly influenced by the blade modeling.

## SUMMARY

A new method for modeling the non-linear behavior of rotor blades has been achieved. A static and dynamic validation has been performed against a non-linear ABAQUS model. This new method enables accurate prediction of aeroelastic loading and rotor blade dynamics for all operating points. The relevance of the modeling approach has been proven for aeroelastic simulations of the entire wind turbine. The influence of the torsional blade deformation on aeroelastic loads has been demonstrated, and its effect can be quantified for an exemplary design load case that is sensitive to the blade modeling.

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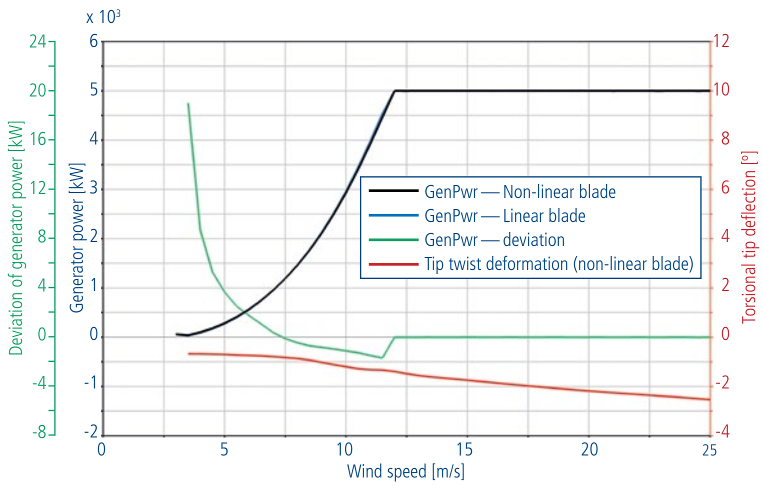


*Fig. 10: Power curve and torsional tip deflection of the UpWind turbine*