Modelling large blade deflections in Bladed

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8th October 2015

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Contents

- Challenges in modelling large blade deflections
- Linear blade model limitations
- Multi-part blade model
  - Comparison to HAWC2
  - Simulation time
- Improving linear model results (Bladed 4.5/4.6)
- Conclusions

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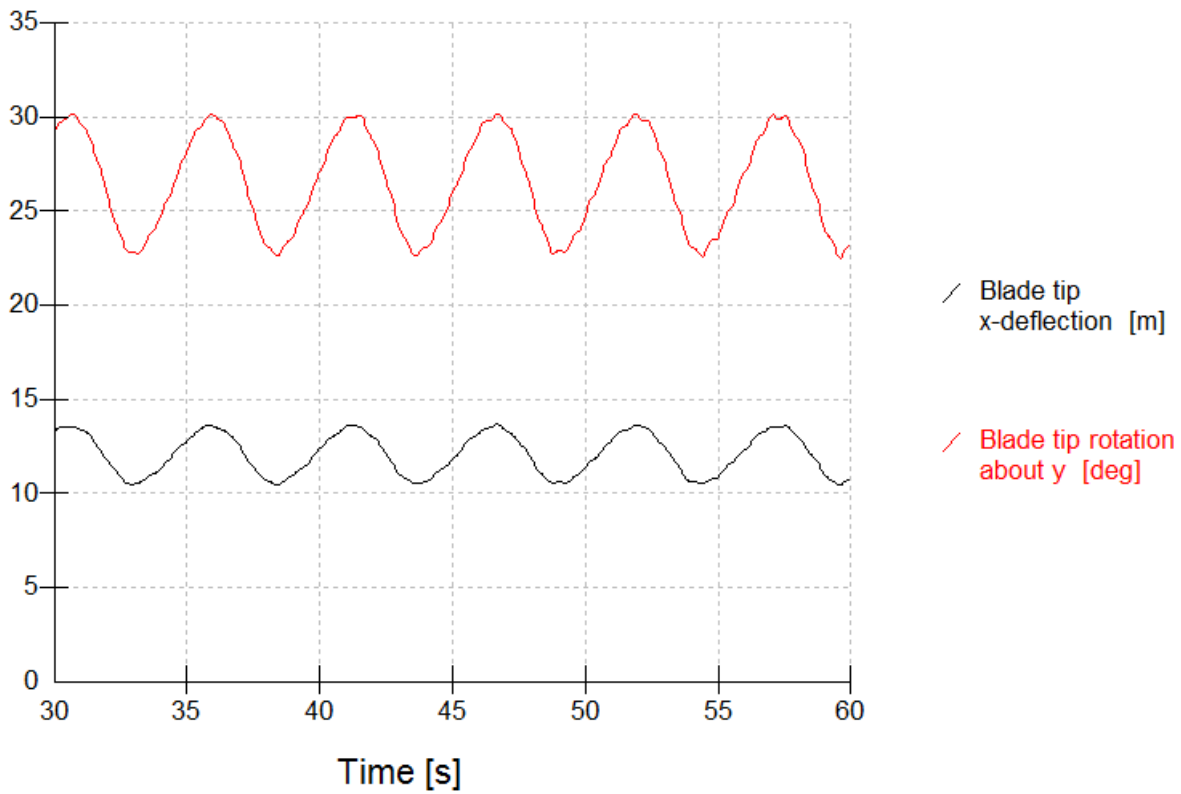
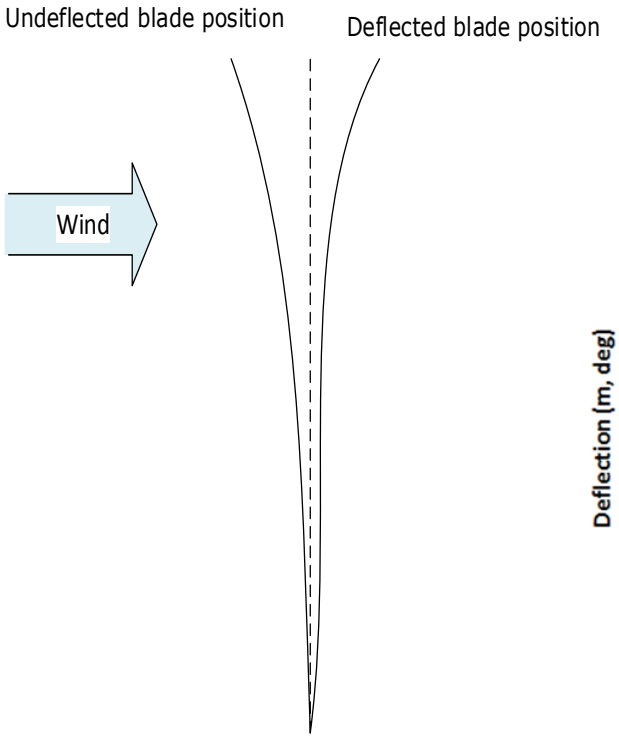
Challenges in modelling large blade deflections

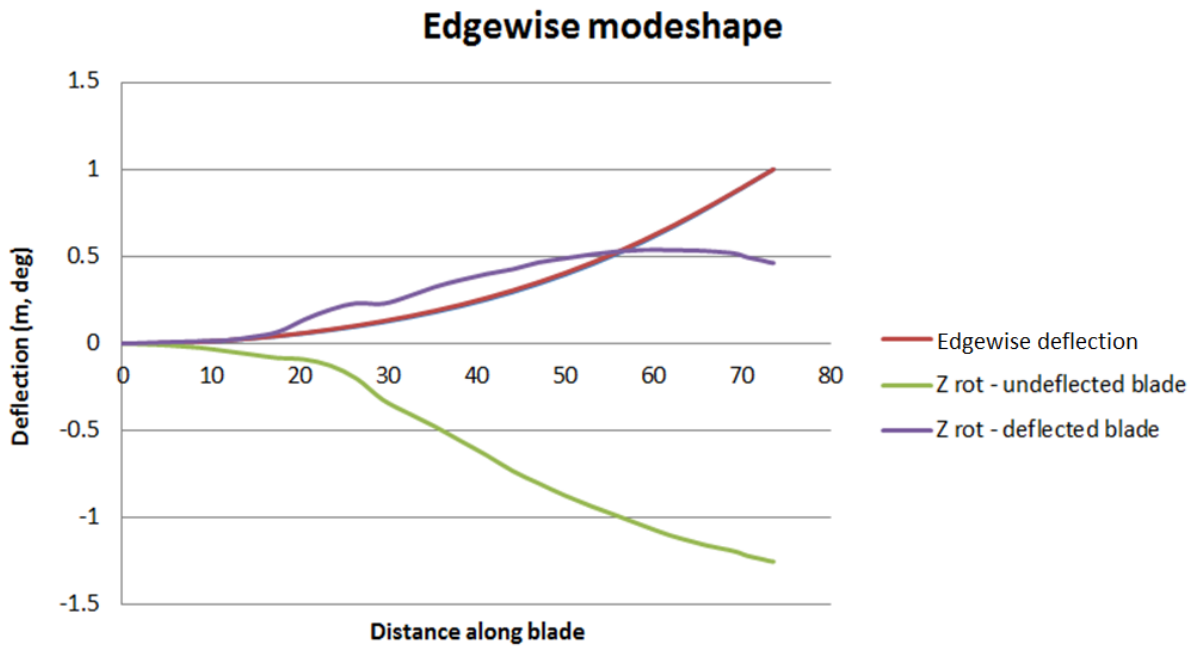
- Some large turbines have very flexible blades
- example 70m blade



Challenges in modelling large blade deflections

- Validity of mode shapes
  - Edgewise mode shape torsional component reverses in deflected blade position





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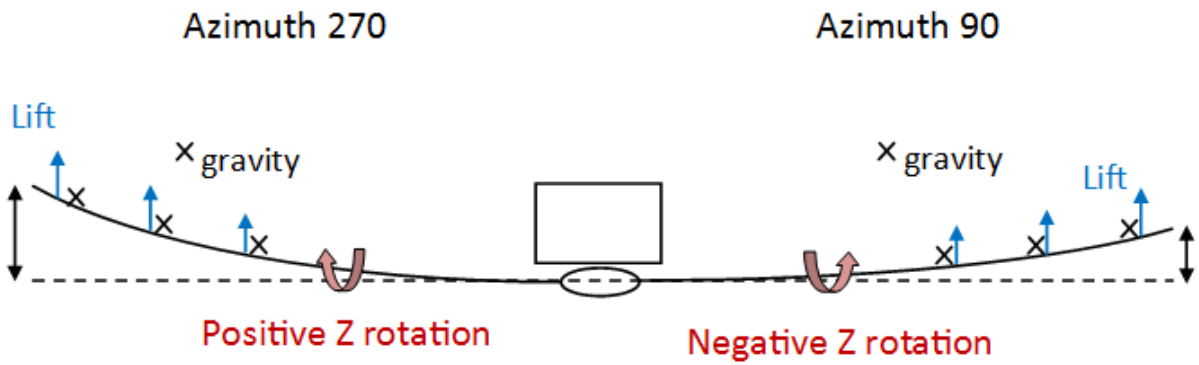
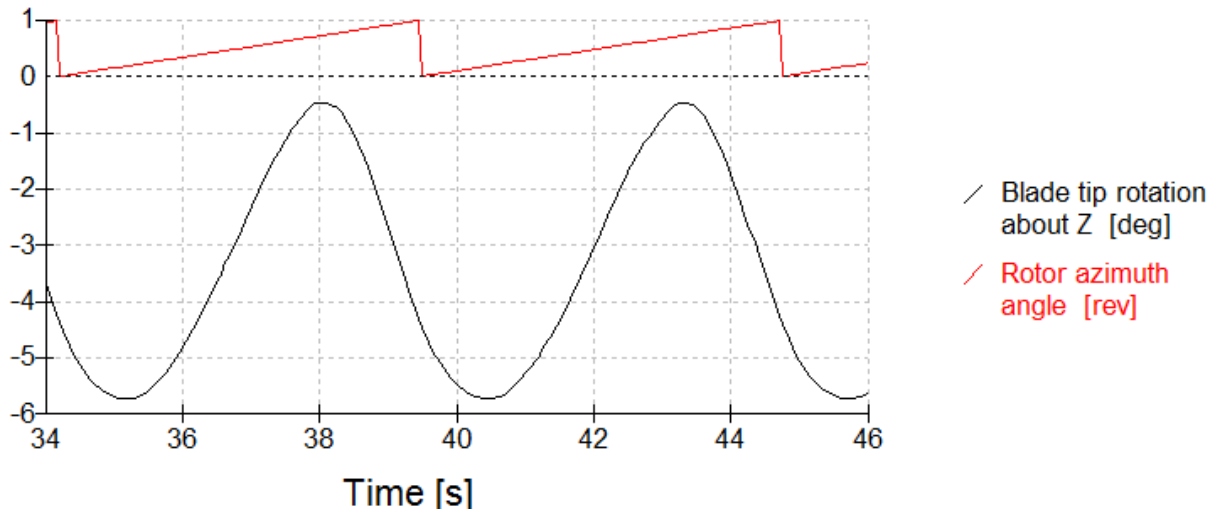
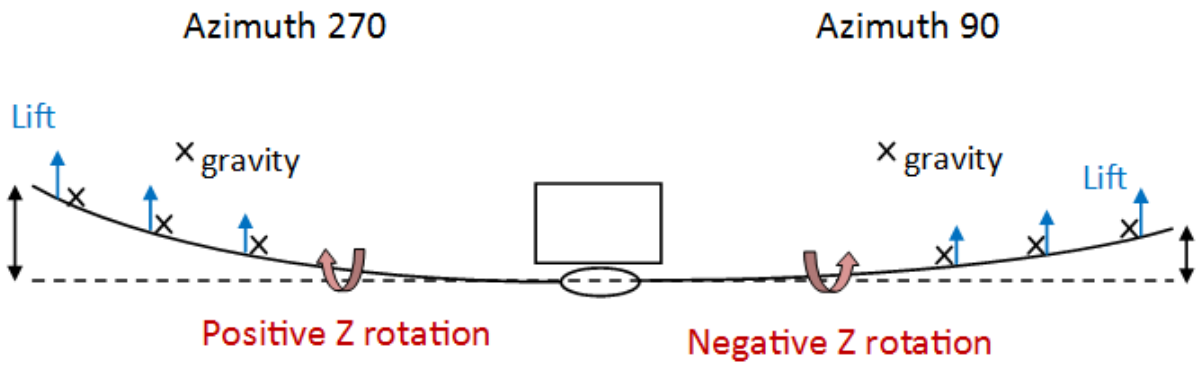
Challenges in modelling large blade deflections

- Lift and gravity loads lead to azimuthal variation in torsion





Challenges in modelling large blade deflections



- Potential for positive feedback if torsion prediction is poor

At azimuth 270

Good torsion model needed!

Positive Z rotation → Increase angle of attack. Increased lift. → Increased blade x-deflection

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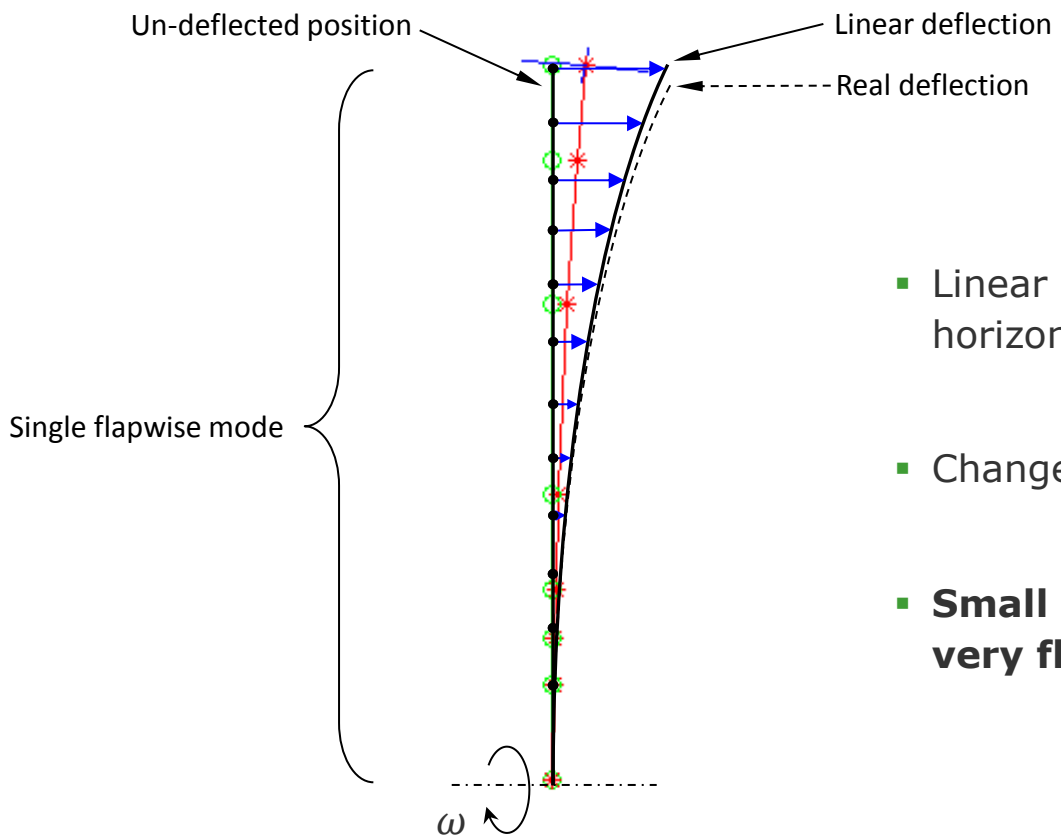
Linear blade model limitations

- Whole-blade linear mode shapes may not capture the deflection well



- Linear modes give bending deflection in horizontal direction (with no blade prebend)
- Change in radial position not accounted for
- **Small deflection assumption not valid for very flexible blades**

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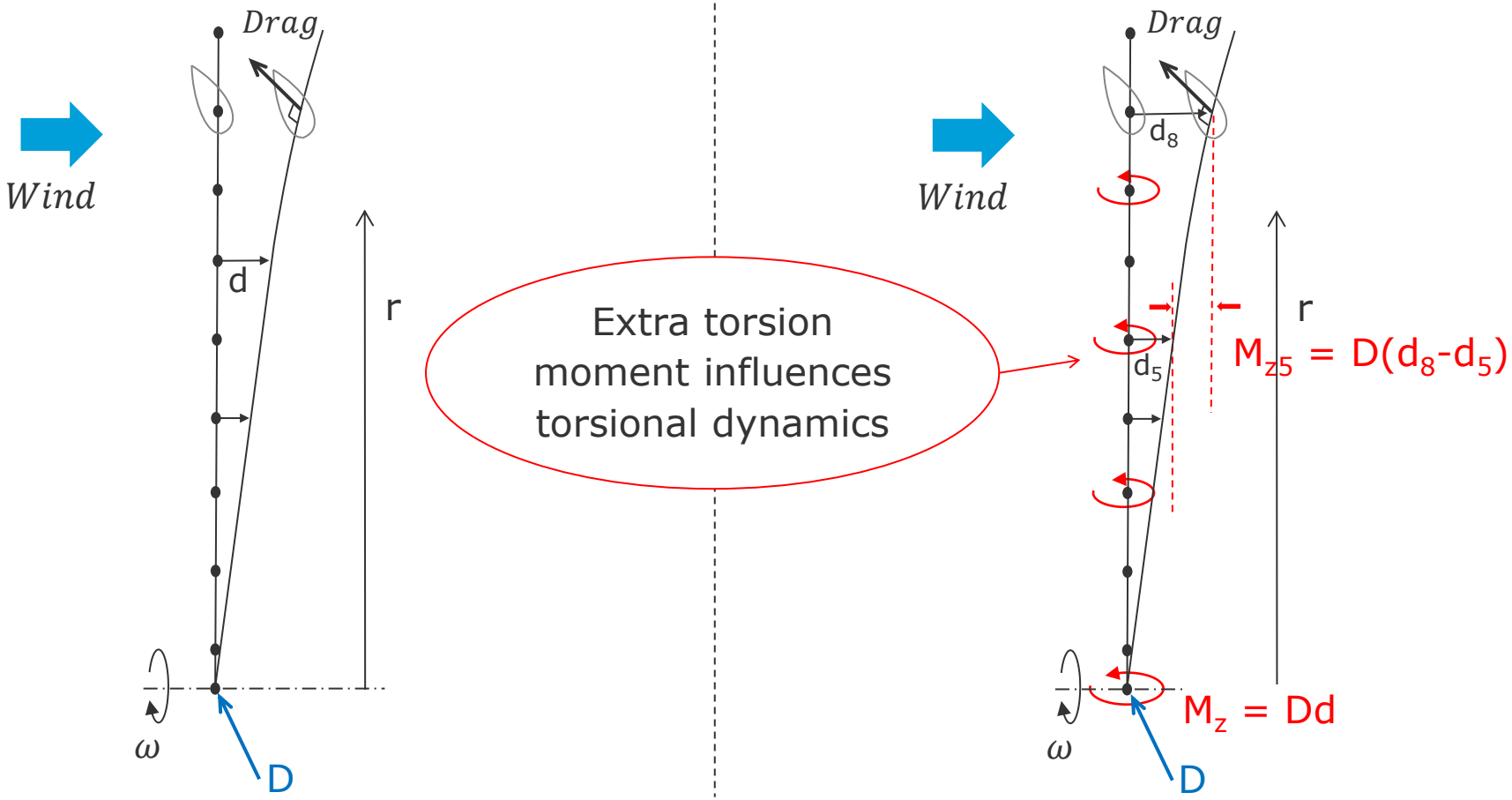
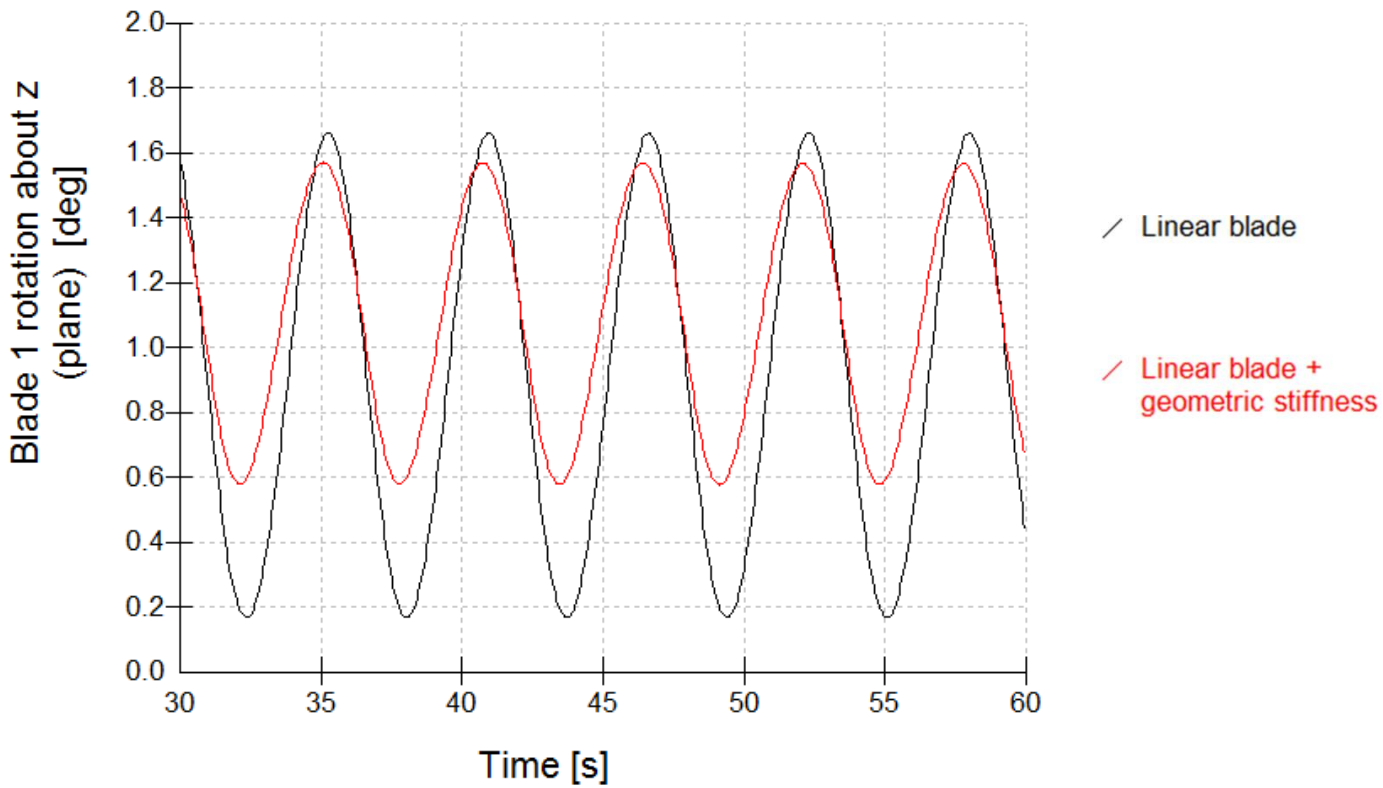
Shear force geometric stiffness

- Linear FE models don't account for deflection from reference state
- Geometric stiffness accounts for the extra moment due to deflection



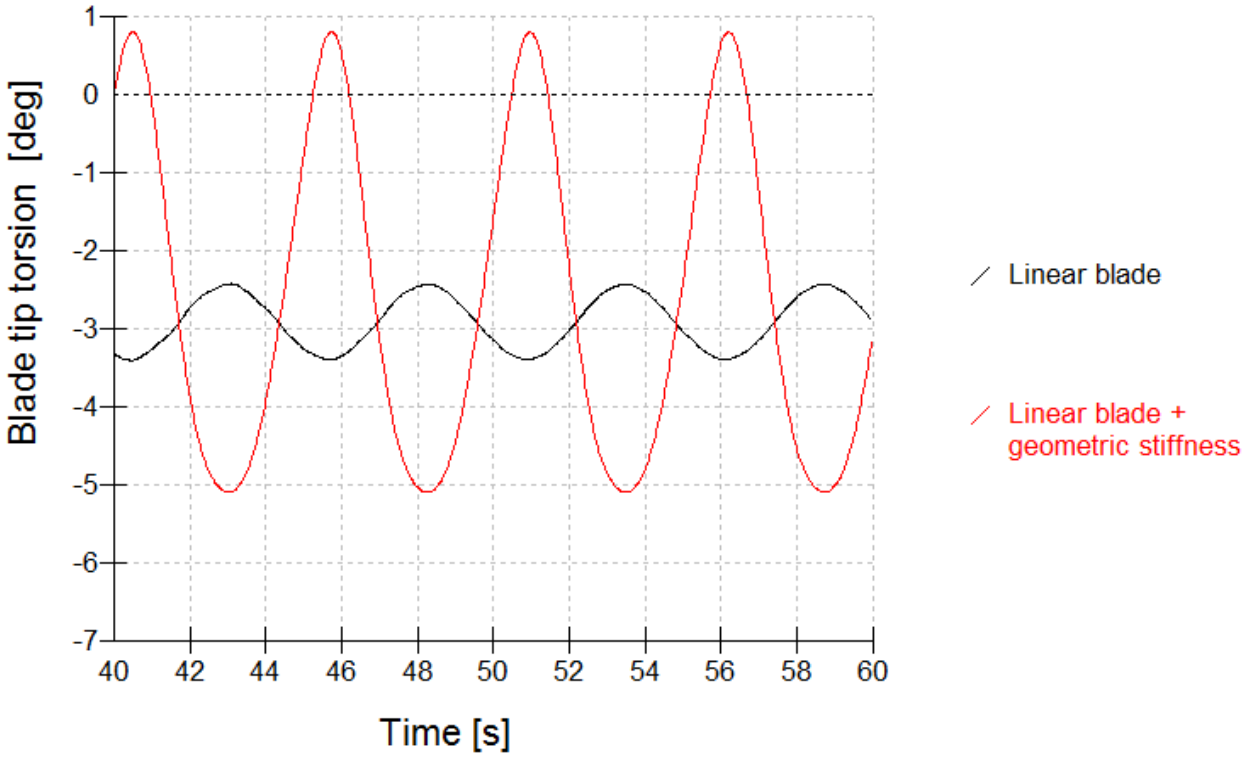
Case 1: stiff blade design

- 78m blade
  - Geometric stiffness model doesn't make that much difference



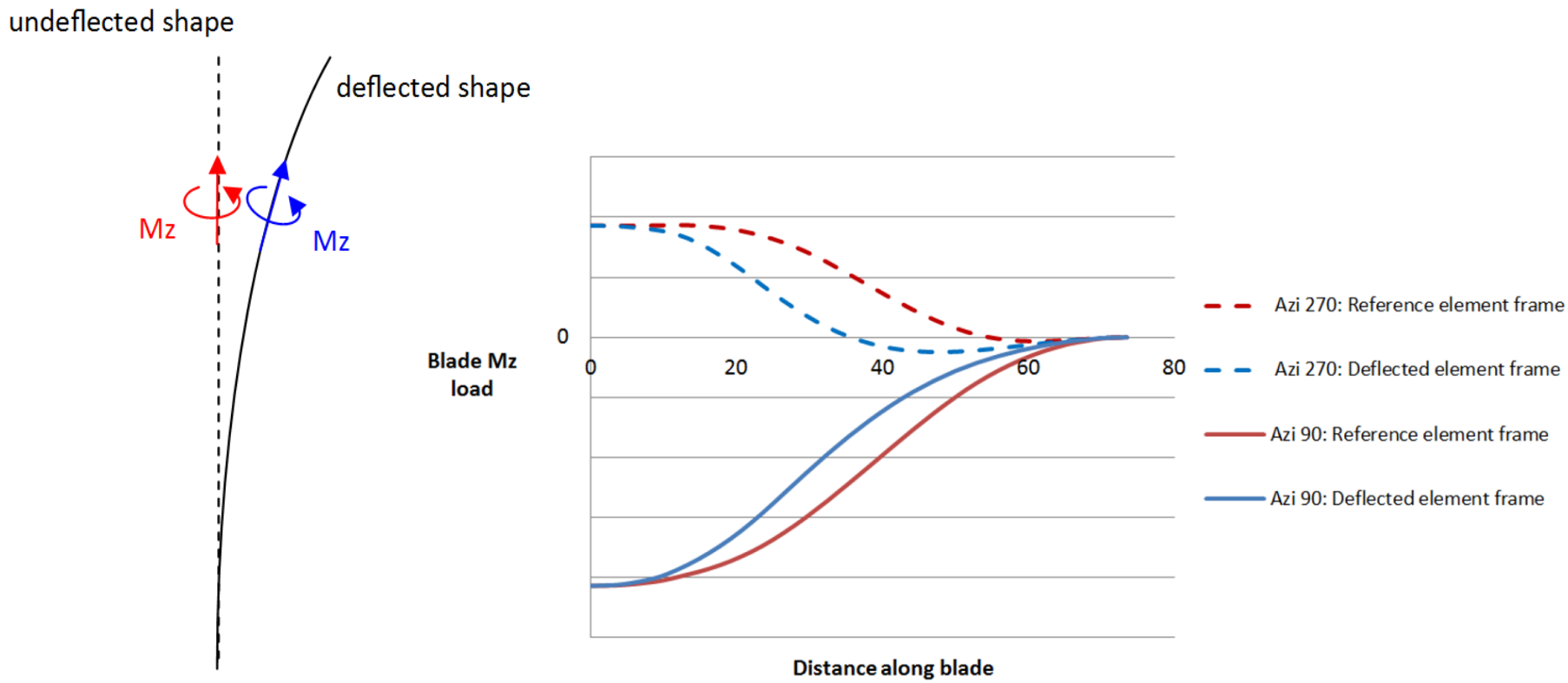
Case 2: flexible blade design

- 73m blade
  - Geometric stiffness strongly influences blade torsion



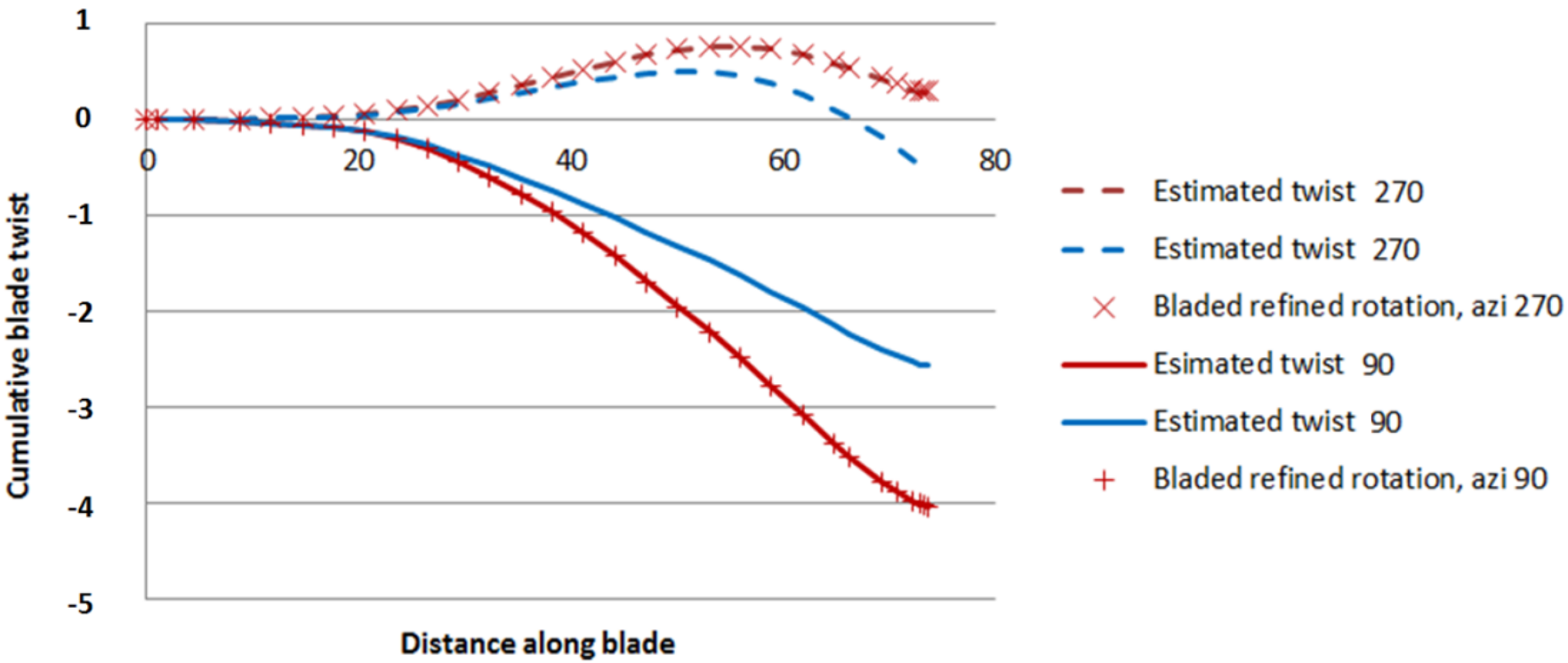
Evaluate linear model accuracy

- To use constant K matrix, dynamic equilibrium evaluated in the undeflected configuration



Linear model accuracy

- This assumption leads to error in blade torsional prediction in very flexible blades



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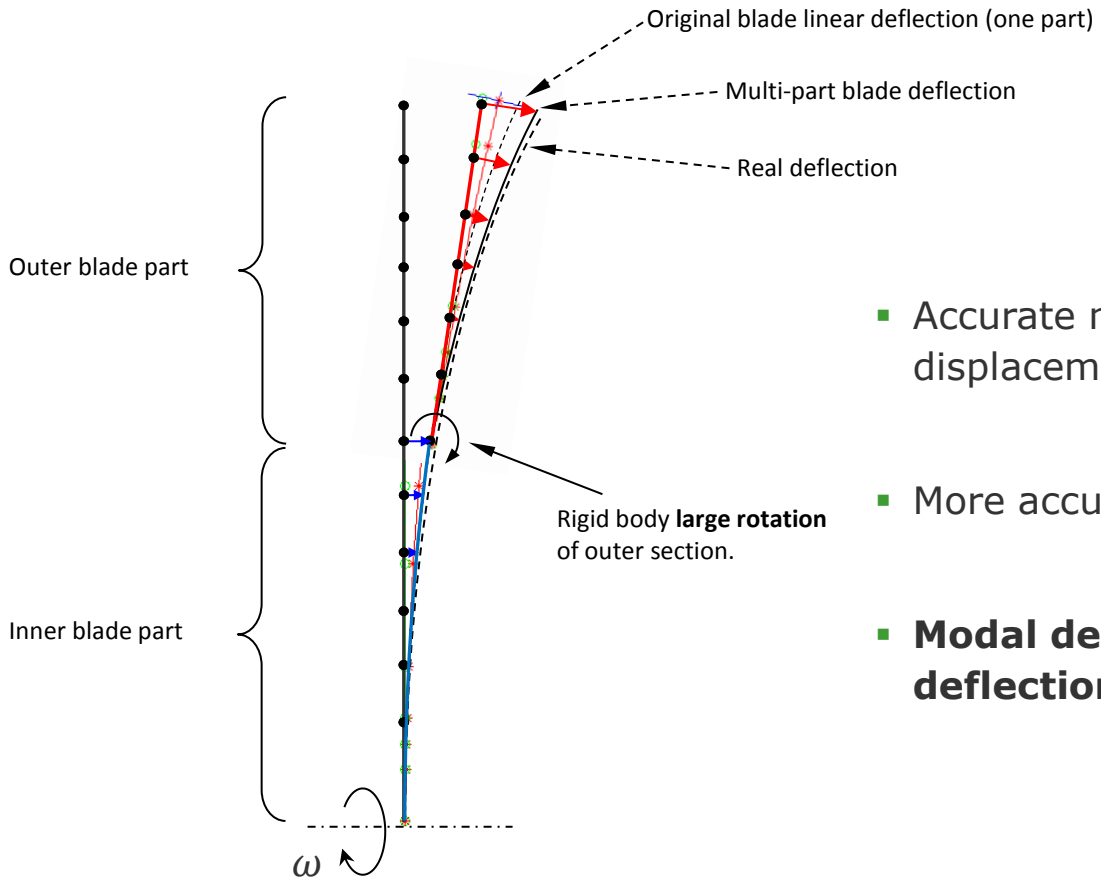
Multi-part blade (Bladed 4.7)

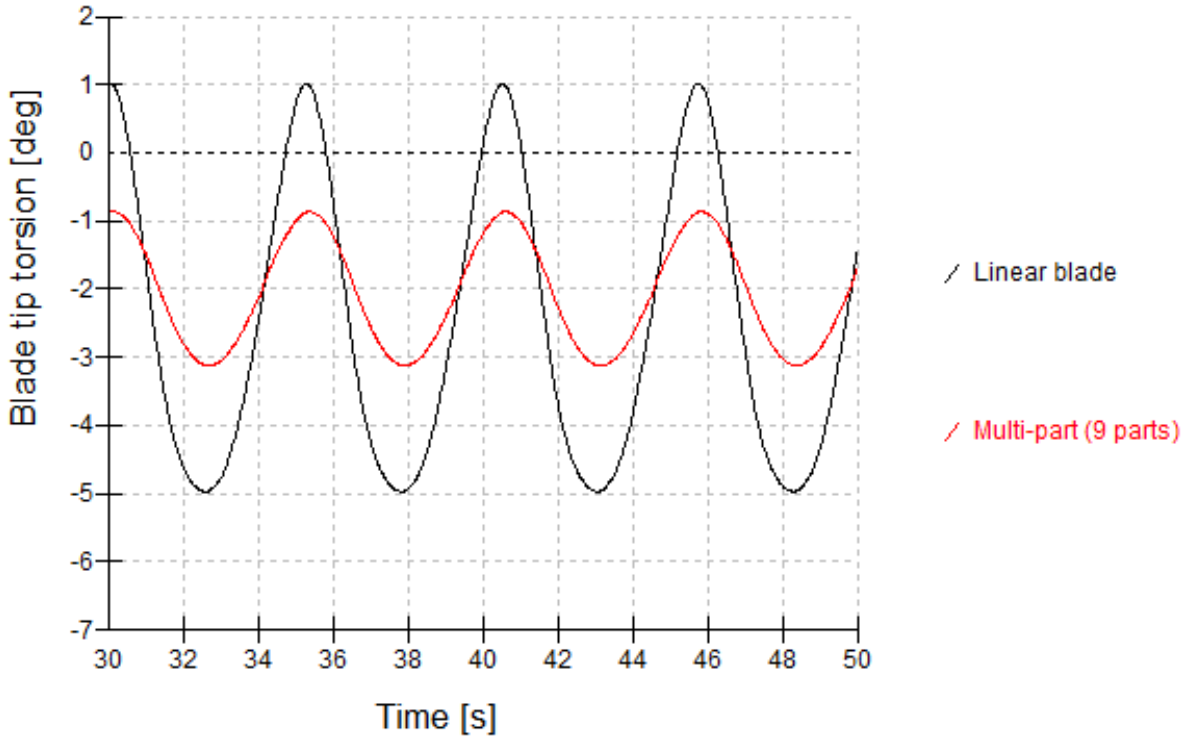
- Blade is several modal bodies



- Accurate model of large (non-linear) displacement, including radial displacement
- More accurate torsion prediction
- **Modal deflections are small, so small deflection assumption is valid**

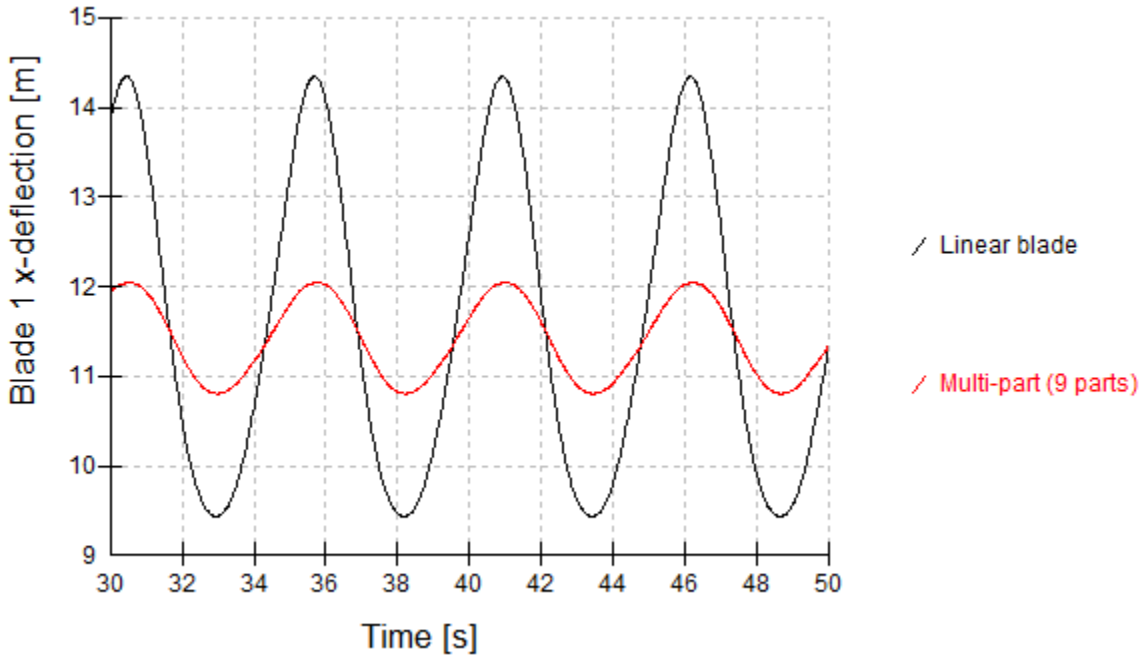
Multi-part blade

- Torsional variation with multi-part is smaller



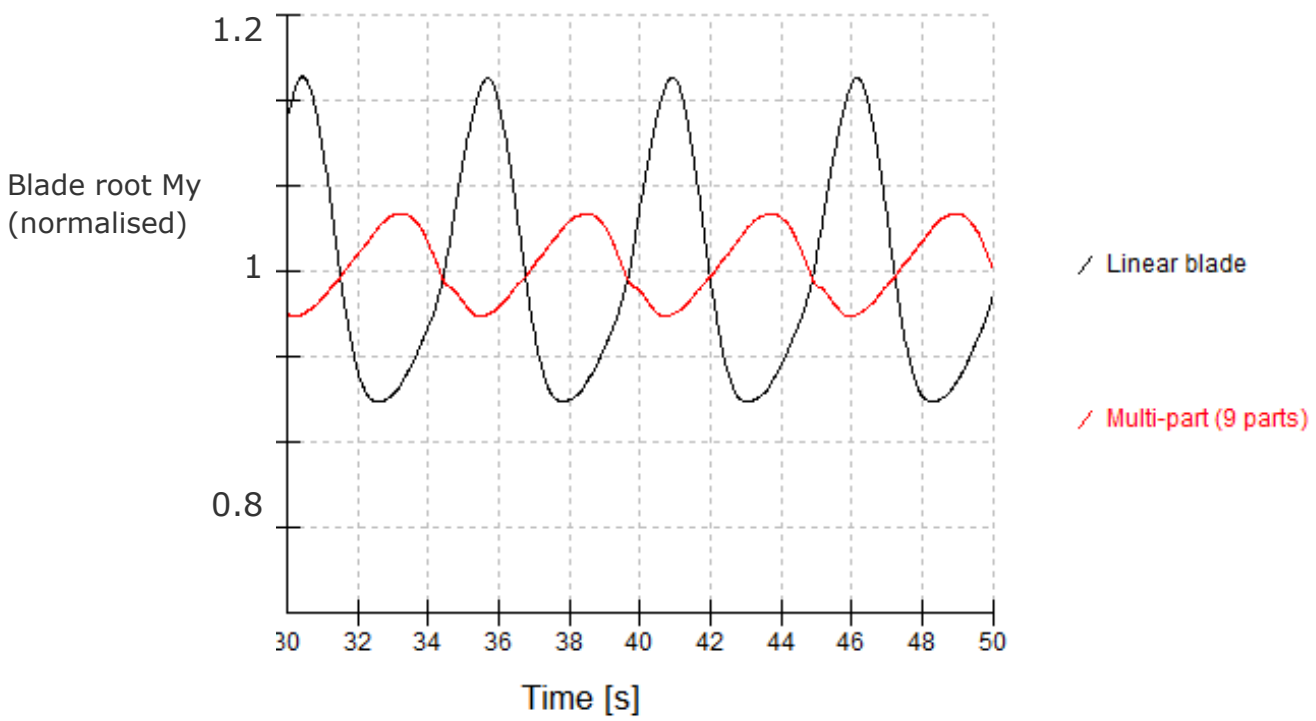
Multi-part blade

- Tip deflection variation with multi-part is smaller

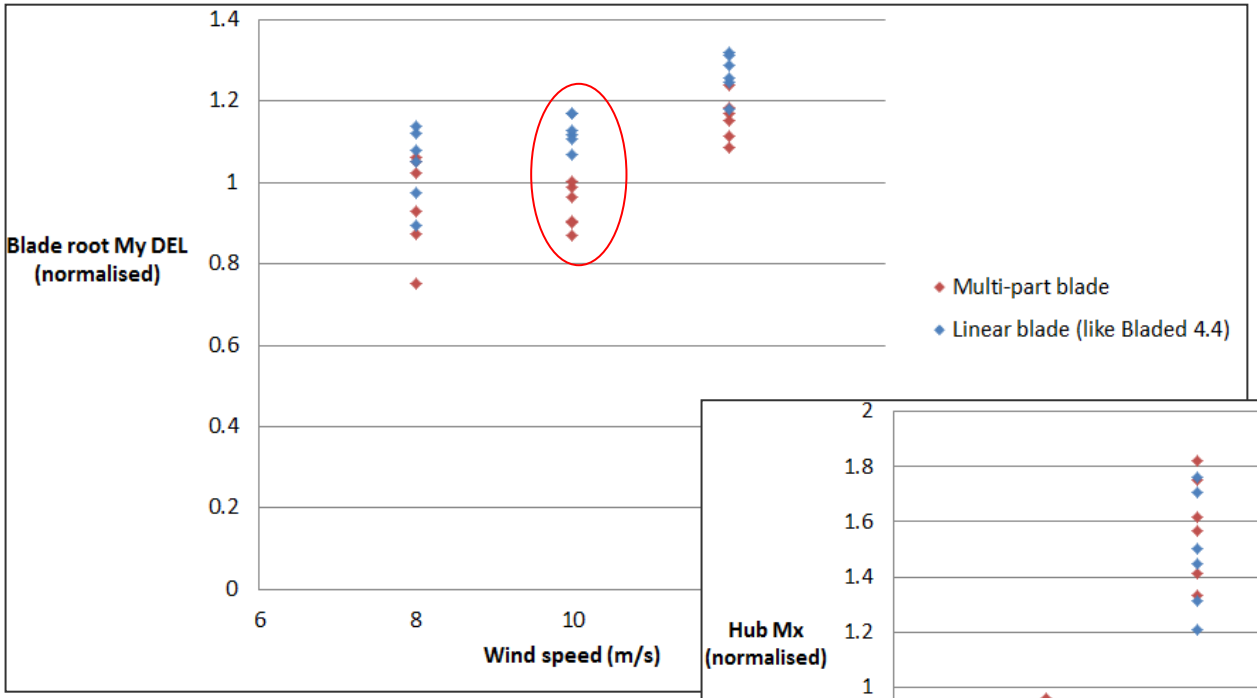


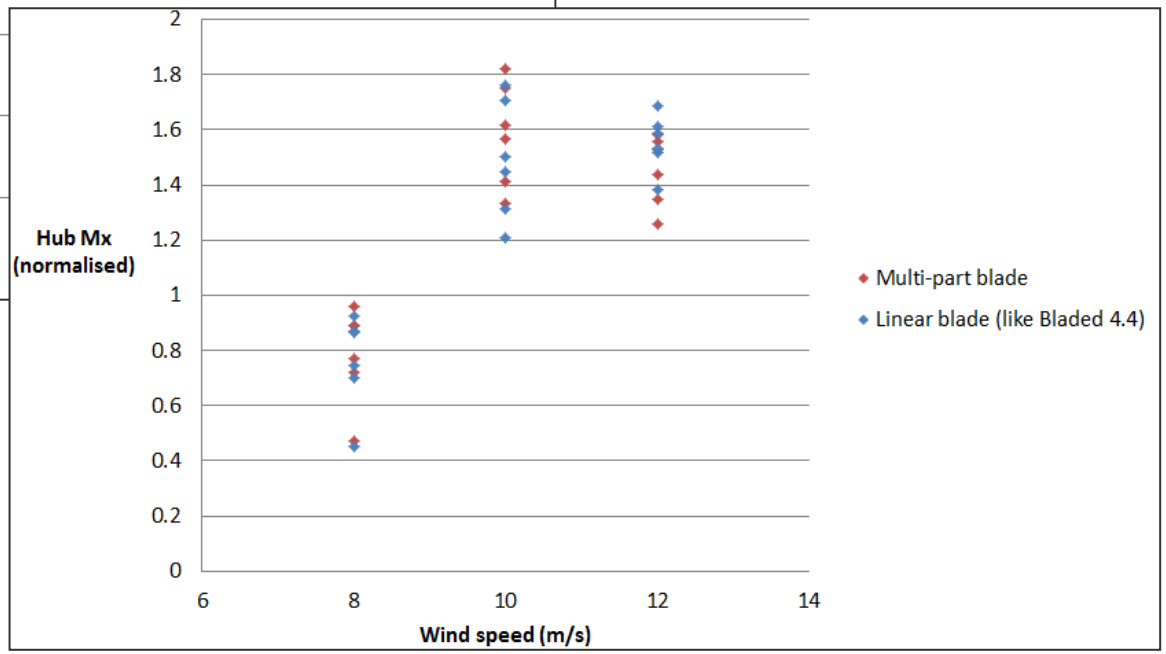
Multi-part blade

- Blade root bending loads…



Comparison of DELs with linear and multi-part model





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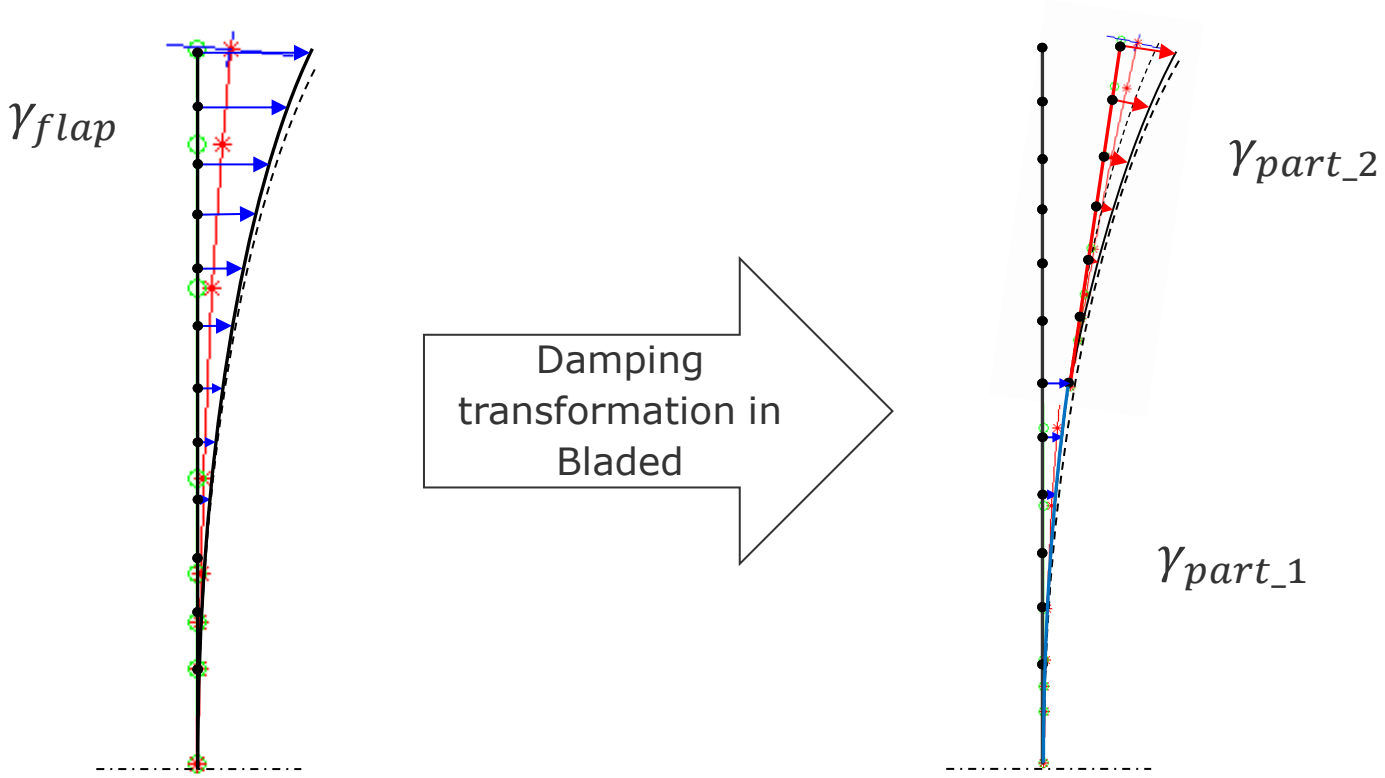
Multi-part blade damping

- User specifies damping for “whole blade” modes



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Comparison to HAWC2 (EWEA 2015 paper preview)

Method:

- Build multi-part models in Bladed and HAWC2 of Alstom Haliade 6MW
- Power production simulations near rated wind speed (steady wind)
- Compare blade deflection and loads

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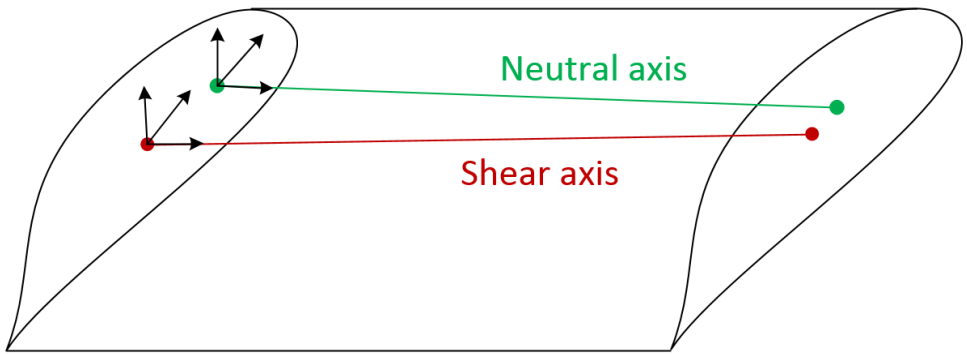
Comparison to HAWC2

- Bladed shear centre orientation correction (SOC) removed for match to HAWC 2



- Extra coupling between bending and torsion moments

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

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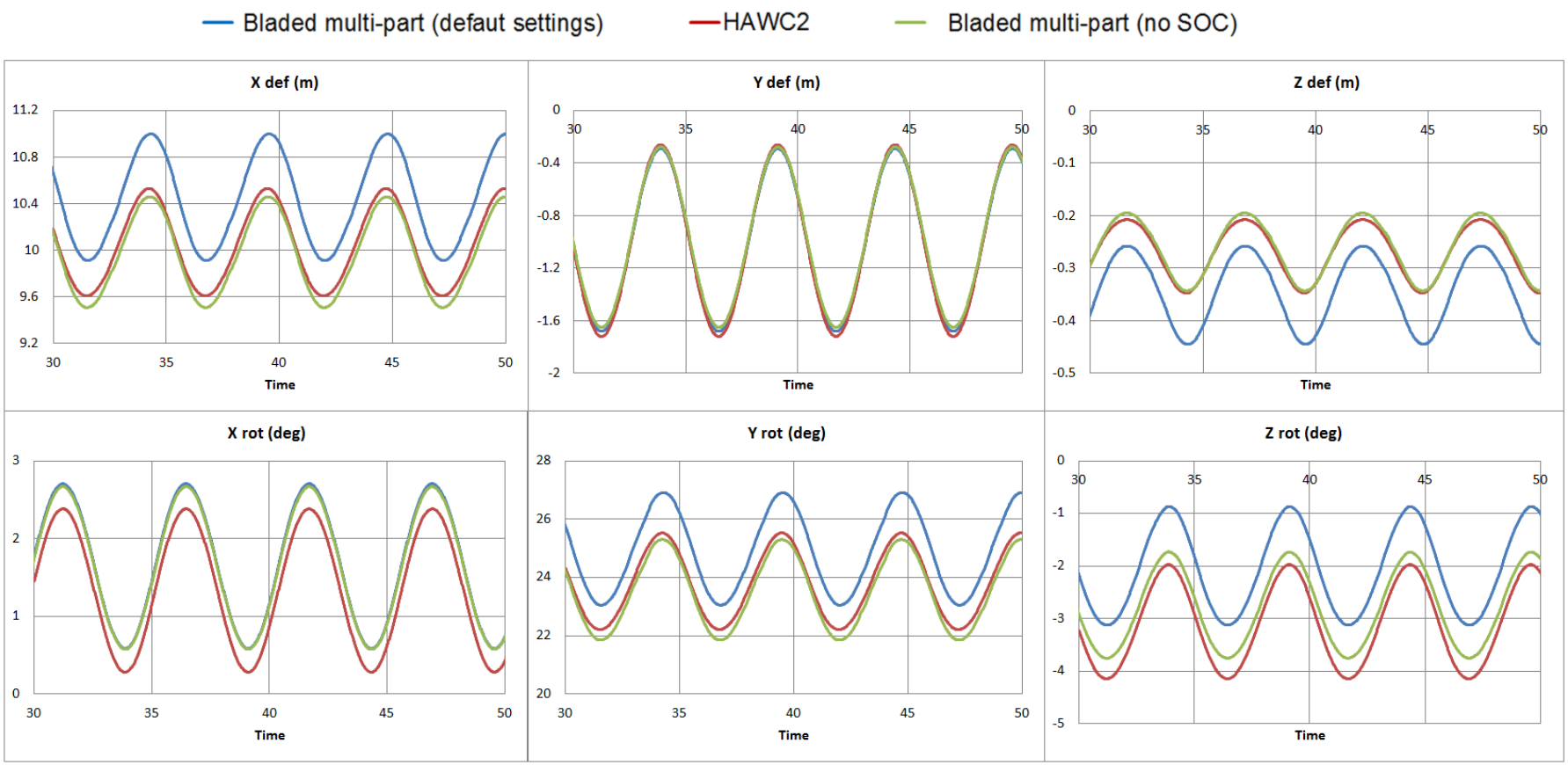
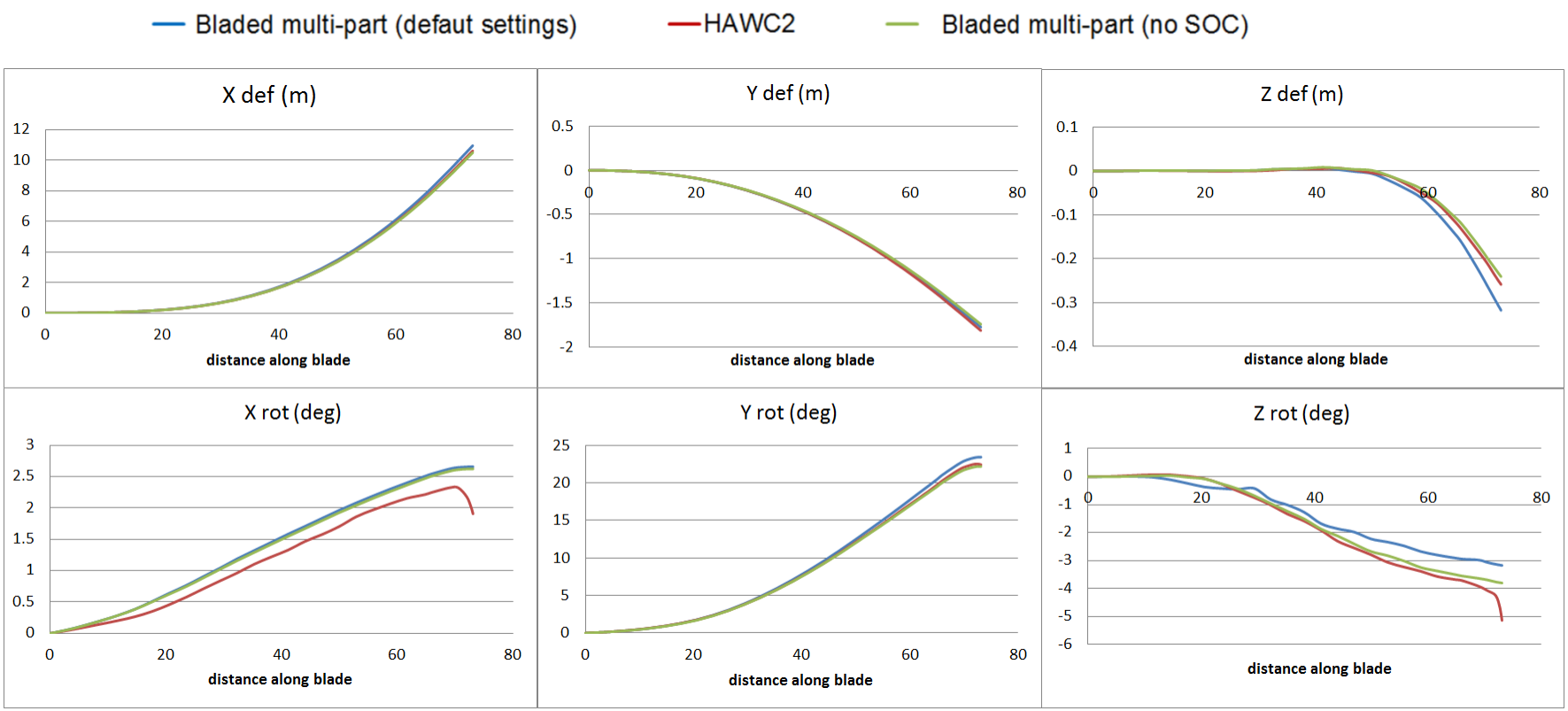
Comparison to HAWC2

- Time history of blade tip deflections in Bladed MultiPart vs. HAWC2



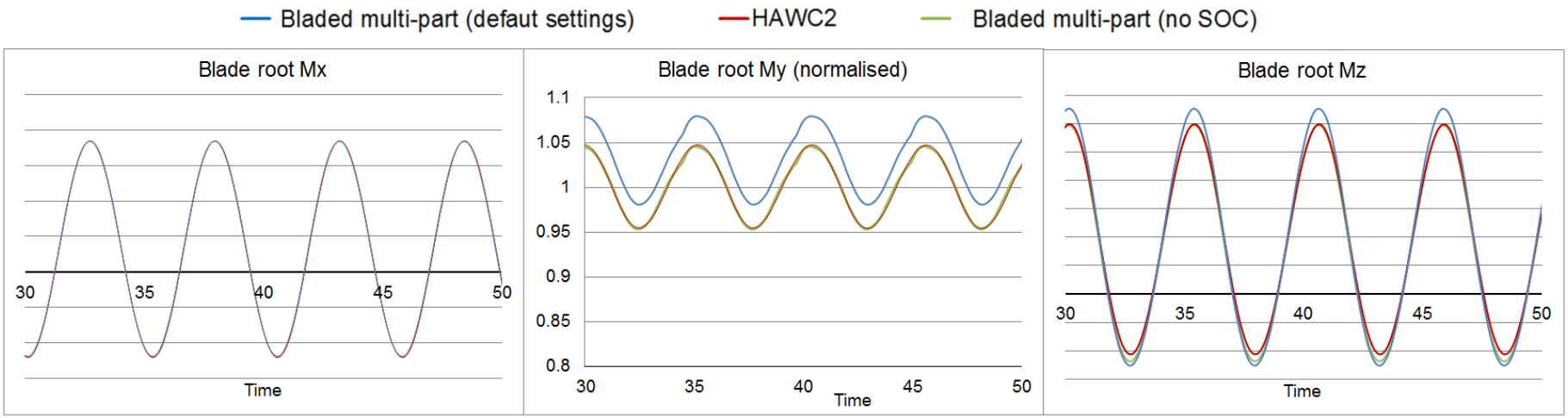
Comparison to HAWC2

- Deflections along blade at time of max Z rotation



Comparison to HAWC2

- Blade root loads comparison



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Simulation time

- Multi-part simulation more computationally expensive
  - more DoF at high frequency

- Time for 10 minute turbulent run…

Model	**Simulation time (minutes)**
Linear blade (Bladed 4.6)	16
Linear blade + geomstiff (Bladed 4.6)	48
MultiPart 5 part (Runge Kutta)	700

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Newmark-β Integrator

- Existing **Runge-Kutta** integrator is *explicit*:
  - *Explicit* = current state (displacement & velocity) calculated from previous time steps

$$x_1 = f(x_0, \dot{x}_0)$$

  - Each structural freedom needs two states: displacement & velocity
  - Very accurate solution but inefficient for high frequencies

- **Newmark-β** integrator is *implicit*
  - *Implicit* = current state determined partly by (unknown) conditions at current time-step.

$$x_1 = f(x_0, \dot{x}_0, \ddot{x}_0, \ddot{x}_1)$$

?

  - Integrates 2nd order states: generates displacement and velocity directly from acceleration

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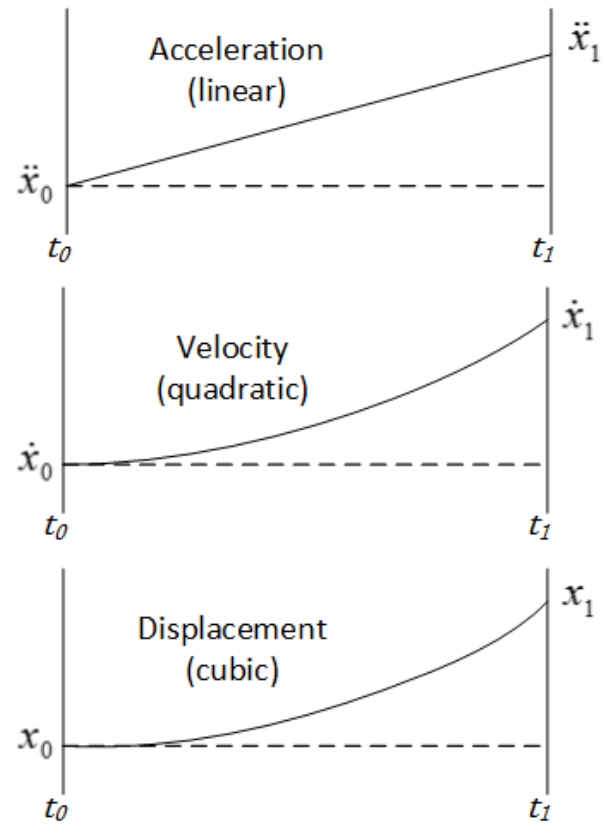
Newmark-β Integrator

- Assumes a particular acceleration function over one step (β=1/6: linear acceleration).

- Implicit nature would normally require iteration
- Converted to explicit integrator by using system matrices $(\boldsymbol{M}, \boldsymbol{C}, \boldsymbol{K}, \boldsymbol{p})$
  - Current acceleration is derived from system matrices and properties at last time-step
  - No need for iteration
  - Time-step is fixed and a user input
  - Allows large time-step even with high (linear) frequencies



$$x_1 = f(x_0, \dot{x}_0, \ddot{x}_0, \ddot{x}_1)$$

$$\ddot{x}_1 = f(x_0, \dot{x}_0, \ddot{x}_0, \boldsymbol{M}, \boldsymbol{C}, \boldsymbol{K}, \boldsymbol{p})$$

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Simulation time

- Multi-part simulation more computationally expensive
  - more DoF at high frequency

- Time for 10 minute turbulent run…

Model	**Simulation time (minutes)**
Linear blade (Bladed 4.6)	16
Linear blade + geomstiff (Bladed 4.6)	48
MultiPart 5 part (Runge Kutta)	700
MultiPart 5 part (Newmark Beta)	44
MultiPart 5 part (Bladed 4.8)	**20**

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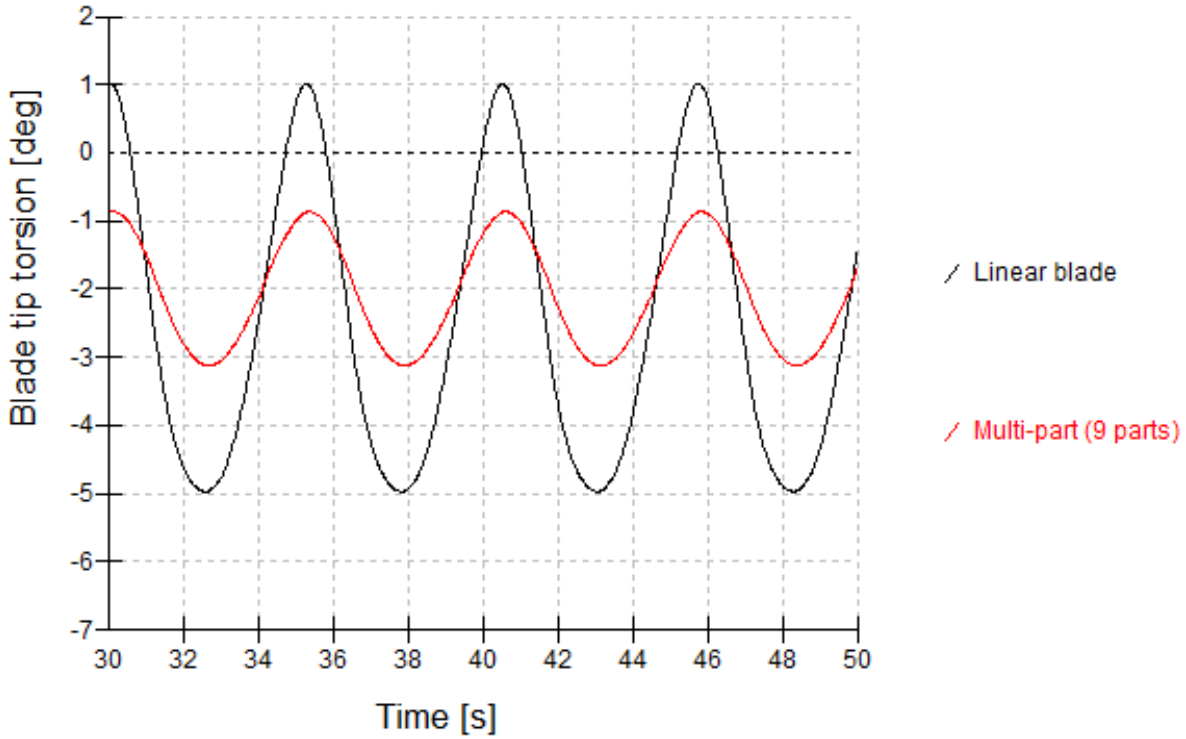
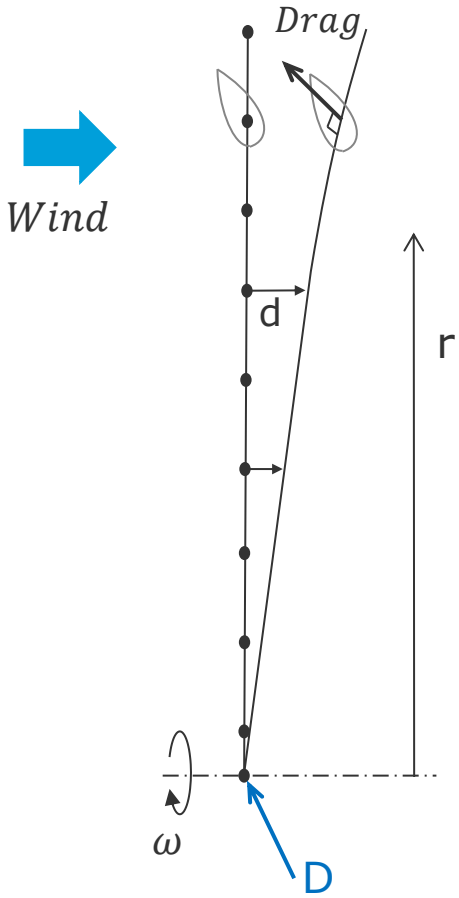
Improving the linear model (for Bladed 4.5/4.6)

- Can the linear results be improved without multi-part blade?

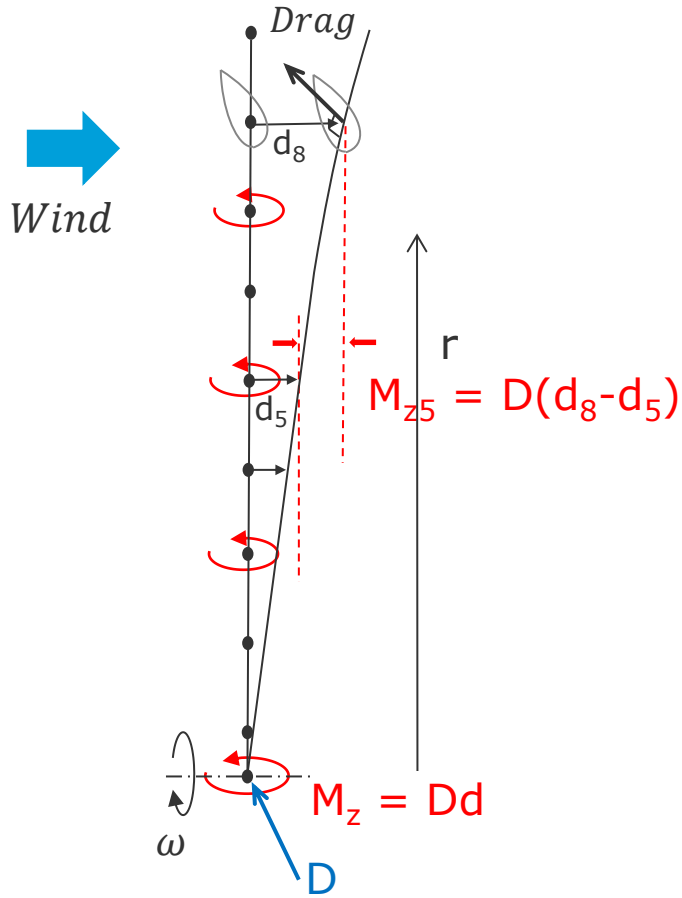


Improving the linear model (for Bladed 4.5/4.6)

- Linear FE models don't account for deflection from reference state



- Geometric stiffness accounts for the extra moment due to deflection



"Tuned" linear model for Bladed 4.5/4.6

- Geometric loads are transformed onto modal DoFs

$$F_{modal} = \Psi^T F_{nodes}$$

$$F_{modal} = \begin{bmatrix} F_{flap} \\ F_{edge} \\ . \\ . \end{bmatrix} \updownarrow \text{No. modes} \qquad \text{and} \qquad F_{nodes} = \begin{bmatrix} F_{1x} \\ F_{1y} \\ . \\ . \end{bmatrix} \updownarrow 6 * \text{No. nodes}$$

- Weighting factor can be applied to torsional mode loads

$$F_{torsion_tuned} = A * F_{torsion_orig}$$

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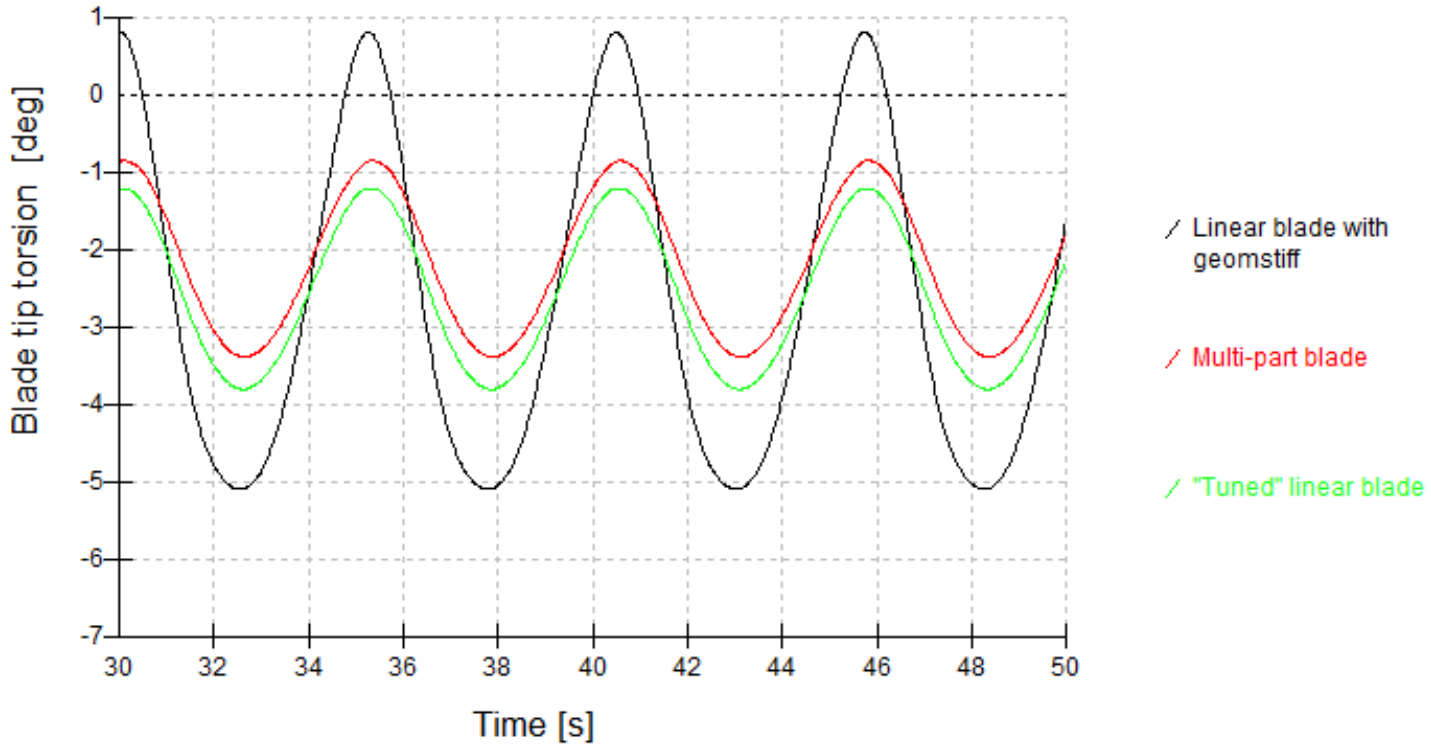
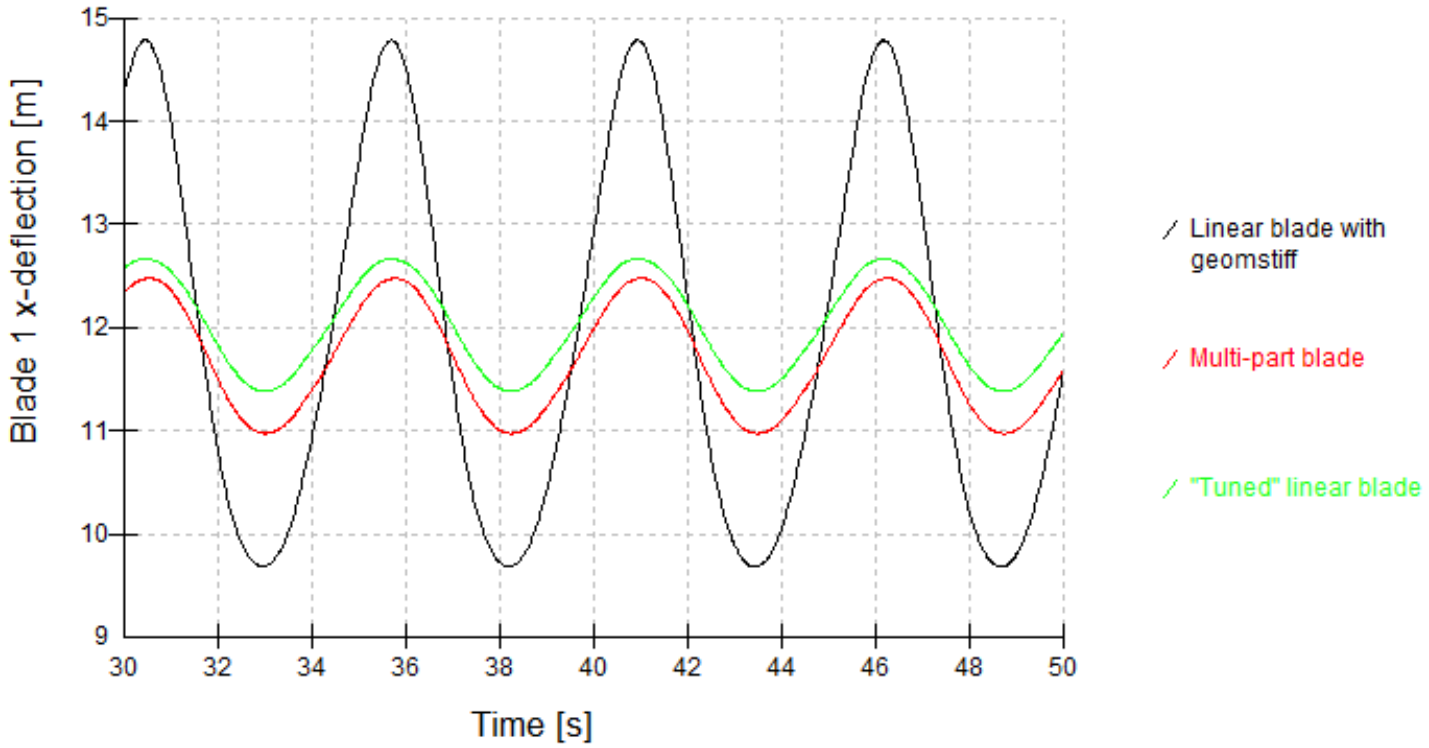
"Tuned" linear model for Bladed 4.5/4.6

- Linear blade model can be "tuned" to behave like the non-linear model
  - weighting factor applied to geometric stiffness force on torsional mode



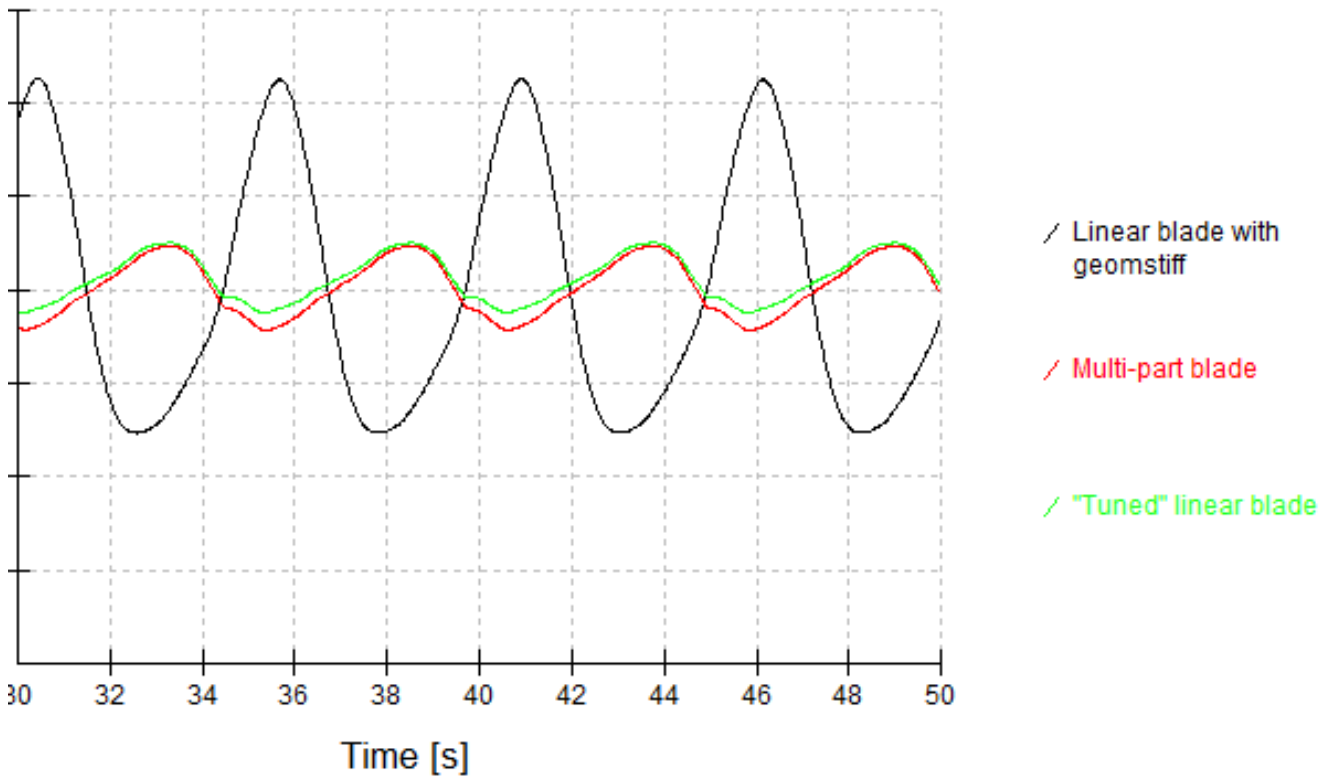
"Tuned" linear model for Bladed 4.5/4.6

- Good match in x-deflection



“Tuned” linear model for Bladed 4.5/4.6

- Blade root bending load



Blade model – options in Bladed

- Bladed 4.0 – 4.4
  - Linear blade, no model for shear geometric stiffness

- Bladed 4.5 ->
  - Linear blade, includes shear geometric stiffness
  - Option to disable shear geometric stiffness
  - A “tuned” model

- Bladed 4.7 ->
  - Multi-part blade

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Conclusions

- Standard linear blade models can't provide an accurate model of a blade undergoing very large deflections
- Multi-part blade model in Bladed 4.7 allows an accurate model of large deflection
- Comparisons between Bladed 4.7 and HAWC2 show good agreement
- Multi-part simulations will be as fast as linear blade simulations in Bladed 4.8!
- Bladed 4.5 and 4.6 have the option of a "tuned" linear blade model to get closer to non-linear model

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Thank you

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