# Results for a Code-to-Code Comparison of alaska/Wind, BLADED, FAST, and FLEX5


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# Introduction

The Institute of Mechatronics developed the multibody simulation software alaska. For the simulation of the dynamic behaviour of complete wind turbines, the add-on module alaska/Wind is available. alaska/Wind contains the full functionality to compute aerodynamic and structural loads on wind turbines. The most of wind turbine computations for design and certification will currently be done with sectoral software tools like GH BLADED, FAST, and FLEX5. These tools have been validated over the years with the help of comparative calculations and measurement results. They are recognized by certification authorities and set the industry standard.

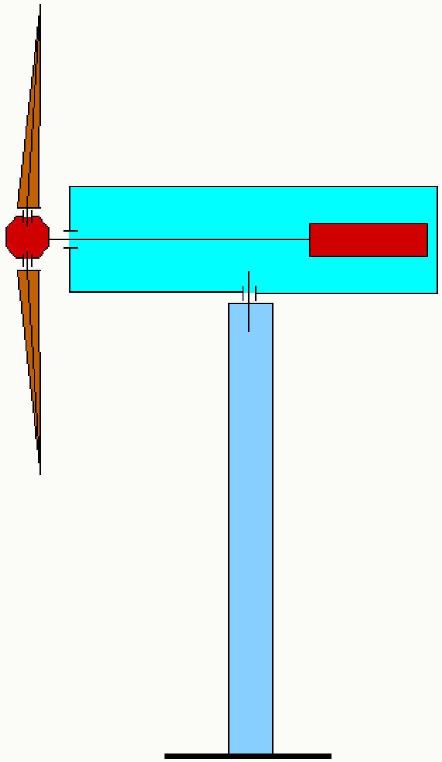
This report is an extension of our validation report [1]. In this document, you will find a short description of every defined load case and all the recorded results for every tested code. Please refer to our validation report for a more detailed description of the test load cases and a evaluation of results.

# Turbine Model



We modeled an approximation of the Nordex N90 turbine using alaska/Wind, BLADED, FAST, and FLEX5. The Nordex N90 is a 2.5 MW, three bladed, pitch controlled variable speed upwind turbine. Because we compared the structural and aerodynamic response of the models, it was much more important to get the same properties of every model rather than an accurate model of the real turbine itself. To reduce the effect of geometric parameters on the aerodynamic response, the turbine model got no cone and tilt angle and the blades were not pre-bent. For the validation of the aerodynamic forces, a simple structural model has been used. It consists of seven rigid bodies (three blades, hub, nacelle, tower, generator), five revolute joints (pitch, yaw, main bearing) and a fixed joint between tower and foundation.

| | |
|---|---|
| Rotor diameter | 90 m |
| Number of blades | 3 |
| Hub height | 78.5 m |
| Tower height | 77 m |
| Rotor shaft tilt angle | 0 ° |
| Blade cone angle | 0 ° |
| Gearbox ratio | 71.8 |



# Model Outputs



| Name | Description | Unit |
|---|---|---|
| MZN | Rotor torque | kNm |
| FZN | Rotor thrust force | kN |
| MXB1 | Blade 1 pitching moment at the blade root, in a coordinate system which does not pitch with the blade | kNm |
| MYB1 | Blade 1 out-of-plane moment at the blade root, in a coordinate system which does not pitch with the blade | kNm |
| MZB1 | Blade1 in-plane moment at the blade root, in a coordinate system which does not pitch with the blade | kNm |
| Yaw Mx | Tower-top yaw bearing yaw moment | kNm |
| Yaw My | Nonrotating tower-top yaw bearing pitch moment | kNm |
| Yaw Mz | Nonrotating tower-top yaw bearing roll moment | kNm |
| VNAV | Total hub-height wind speed magnitude | m/s |
| NRot | Rotor speed | rpm |
| Tip deflection flapwise | Blade 1 tip deflection flapwise | m |
| Tip deflection edgewise | Blade 1 tip deflection edgewise | m |

Institut für Mechatronik

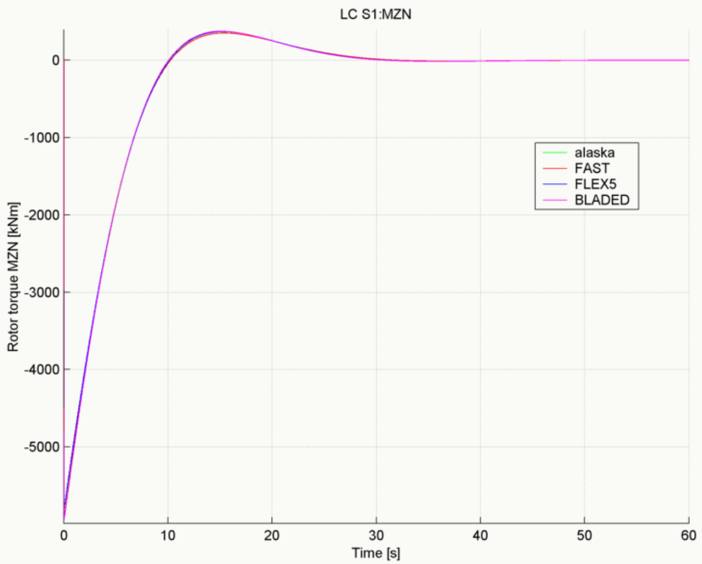
## LCGroup I_Structure
## Structural Load Cases

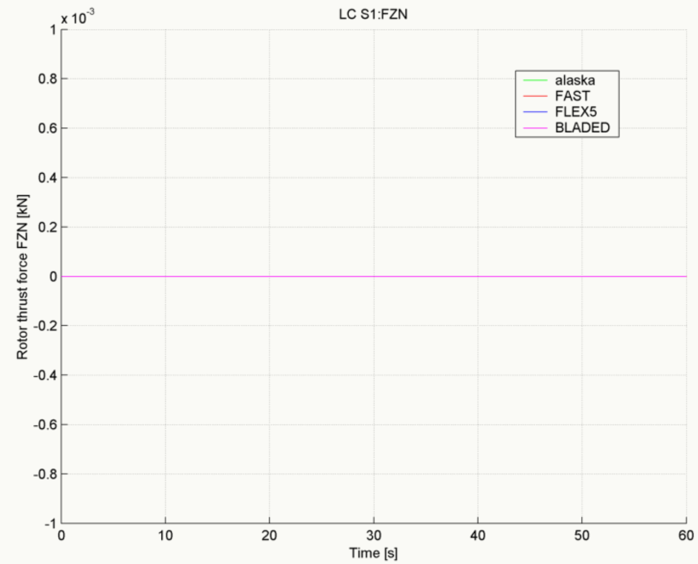
| LC Id | Turbine Model | | | | | | | | | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aerodynamic Forces | Linearized Model | Gravity | Rotor DOF | Blade DOF 2 Flap, 1 Edge | Tower DOF 2 side-to-side 2 fore-aft | Pitch | Yaw | Rotor IC | Generator / Motor | Demanded Rotor Speed | Time Step | $T_{total}$ |
| | on/off | on/off | on/off | on/off | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | [rpm] | [s] | [s] |
| S1 | off | off | off | on | off | off | fixed, 0° | fixed, 0° | 0 | on | 15 | 0,02 | 60 |
| S2 | off | off | off | off | off | off | controlled | fixed, 0° | 0 | off | - | 0,02 | 60 |
| S3 | off | off | off | off | off | off | fixed, 0° | controlled | 0 | off | - | 0,02 | 60 |
| S4 | off | on | off | off | on | off | fixed, 0° | fixed, 0° | 0 | off | - | 0,02 | 0 |
| S5 | off | on | off | off | off | on | fixed, 0° | fixed, 0° | 0 | off | - | 0,02 | 0 |

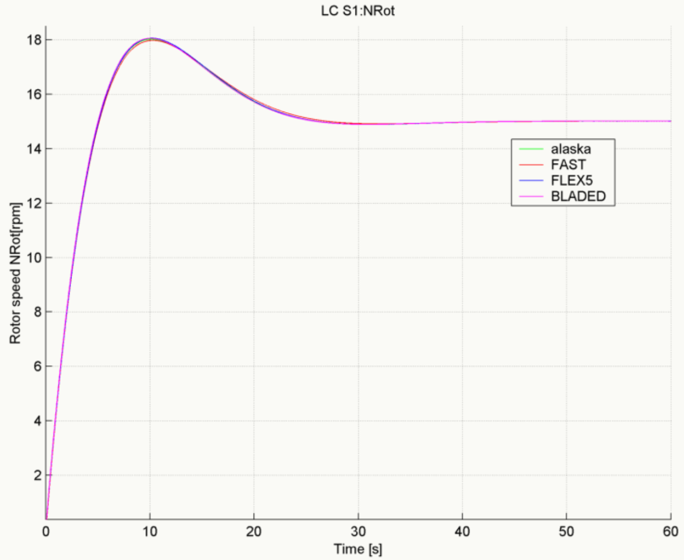
- **Compute aerodynamic forces off**

**The load case group LCGroup I_Structure defines load cases for the validation of the structural model. The computation of aerodynamic forces has been switched off for all models. With the load cases S1-S3, the mass and inertia parameters has been validated. Therefore, a demanded motion has been applied at each joint (rotor, pitch, yaw) by the use of a PI controller. The PI controller has been implemented as a Dynamic Link Library (DLL) in the style of the BLADED code. The codes alaska/Wind and FAST provide a BLADED-style DLL interface. For FLEX5, the PI controller model has directly been implemented in the source code of FLEX5. With the load cases S4 and S5, the elastic blade and tower model has been validated.**

# Load Case LC_S1, Aerodynamic Forces off, Generator is used in a Motor Mode

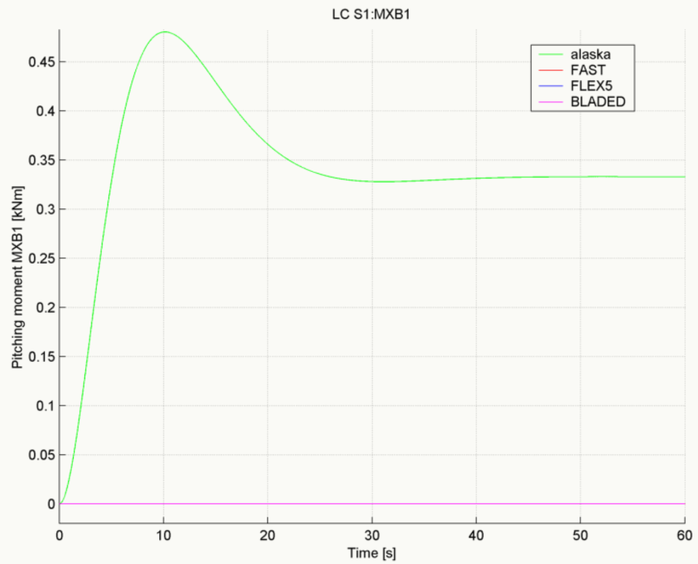


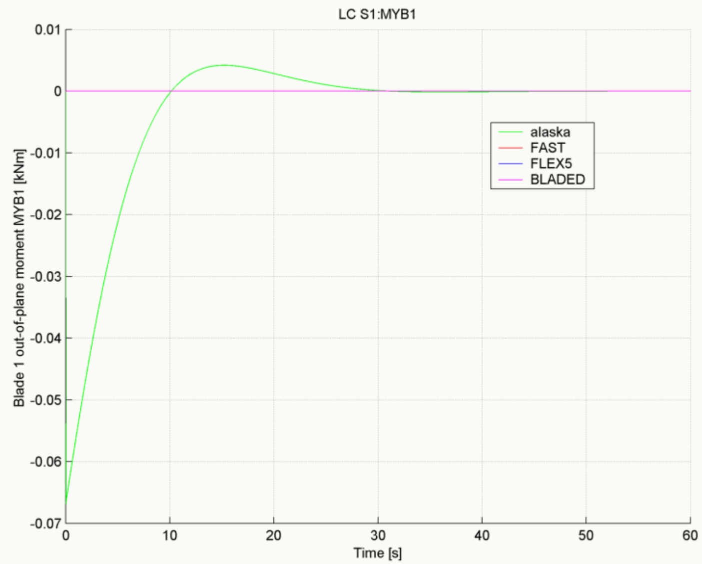



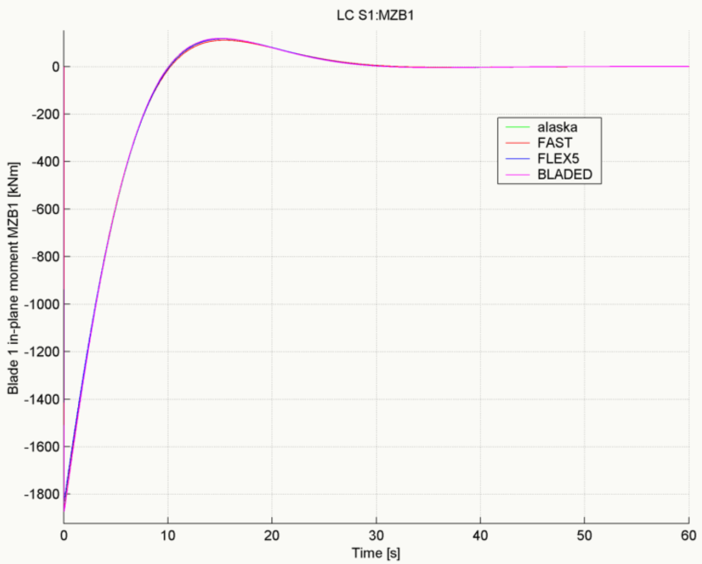




- **the generator is used in a motor mode, the motor torque has been provided by PI speed controller**
- **the motor accelerates the rotor up to a constant rotor speed of 15 rpm**
- **except for the rotor rotational degree of freedom all other degrees are locked in the turbine model**

# Load Case LC_S1, Aerodynamic Forces off, Generator is used in a Motor Mode



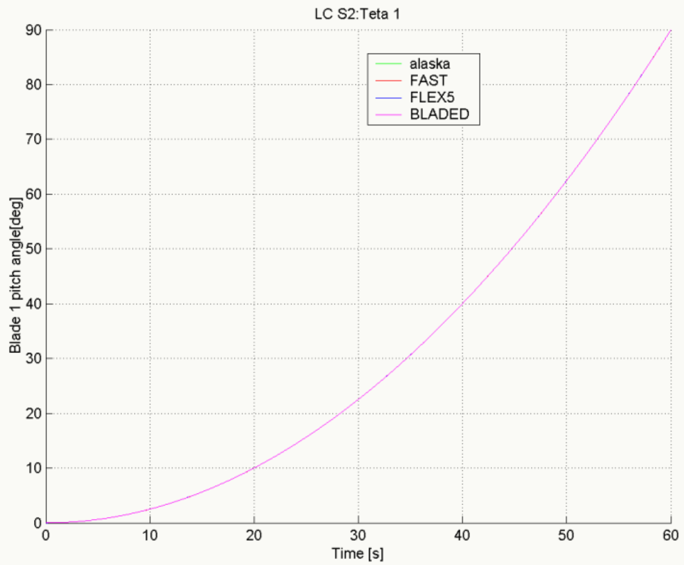

- deviations in out-of-plane moment and pitching moment because of simplified structural blade models in BLADED, FAST, and FLEX5
- missing moments of deviation $J_{23}, J_{32}$
- if a principal axis of the rotor blade does not align with the rotor axis you will get moments of deviation which cause the angular momentum

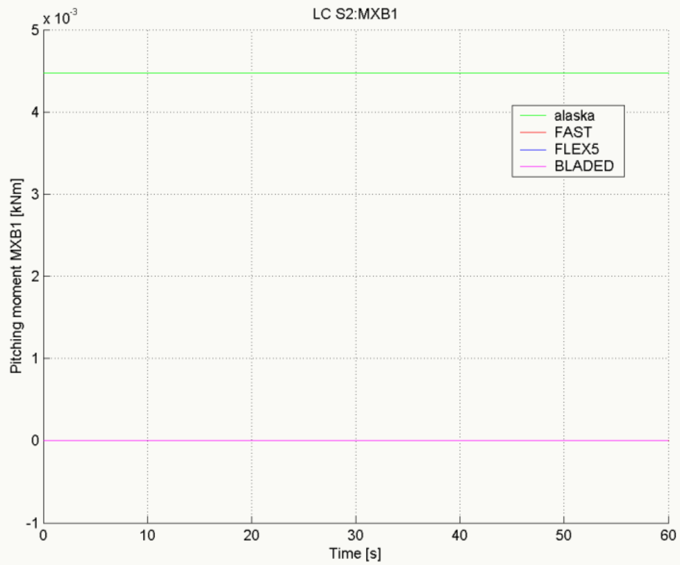
$$M = J\dot{\omega} + \tilde{\omega}J\omega$$

$$M = \begin{bmatrix} -J_{23} \cdot \omega_3^{\;2} \\ J_{23} \cdot \dot{\omega}_3 \\ J_{33} \cdot \dot{\omega}_3 \end{bmatrix}$$

- pitching moment
- out-of-plane moment
- in-plane moment

# Load Case LC_S2, Aerodynamic Forces off, Pitch postion controled



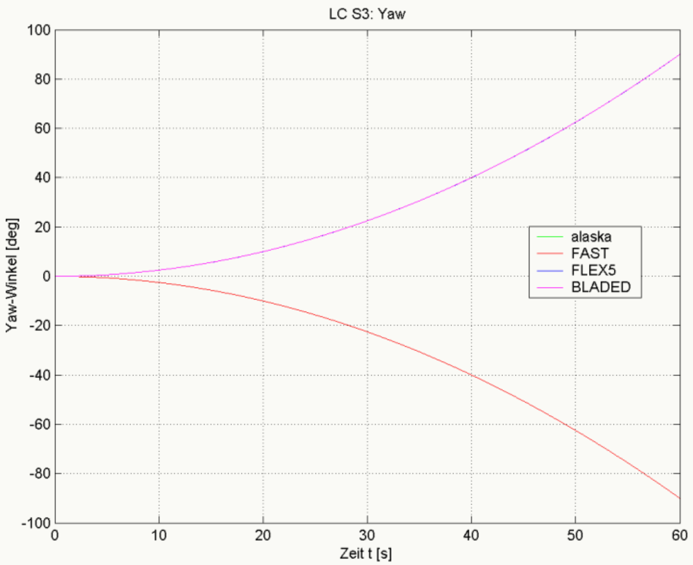



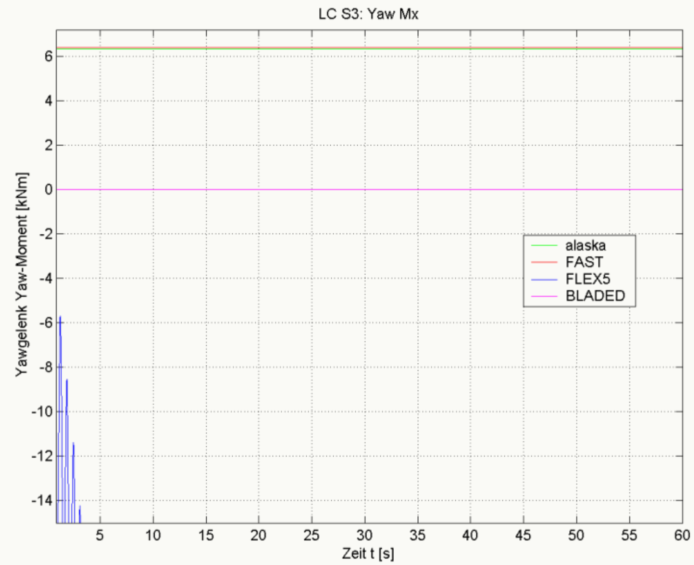

**In load case LC_S2, the model contains only a rotational degree of freedom for the pitch joint. To validate the principal moments of inertia about the blade pitching axis, a constant pitching acceleration was necessary. As you can see, the dynamic of the pitch actuator is only considered in alaska/Wind.**

$$\varphi = \frac{\pi}{7200} \cdot t^2$$

$$\dot{\varphi} = \frac{\pi}{3600} \cdot t$$

$$\ddot{\varphi} = \frac{\pi}{3600}$$



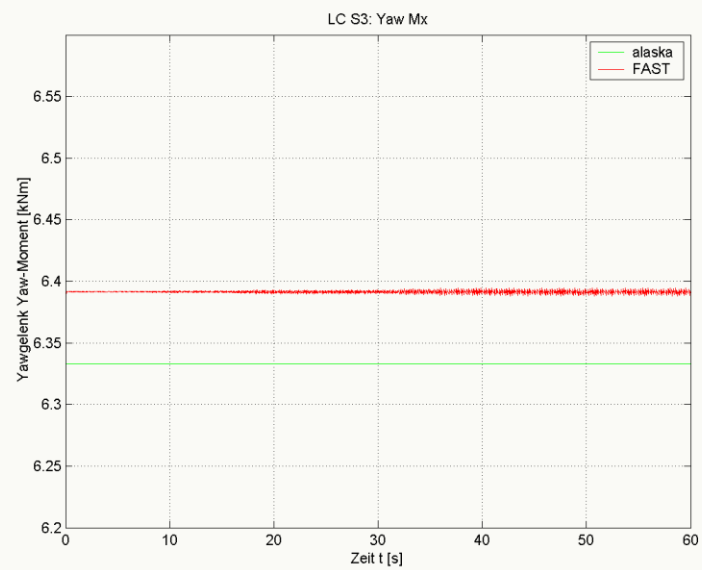




In load case LC_S3, the model contains only a rotational degree of freedom for the yaw joint. For validation the principal moments of inertia about the yaw, pitch, and roll axis, a constant yaw acceleration was necessary.

$$\varphi = \frac{\pi}{7200} \cdot t^2$$

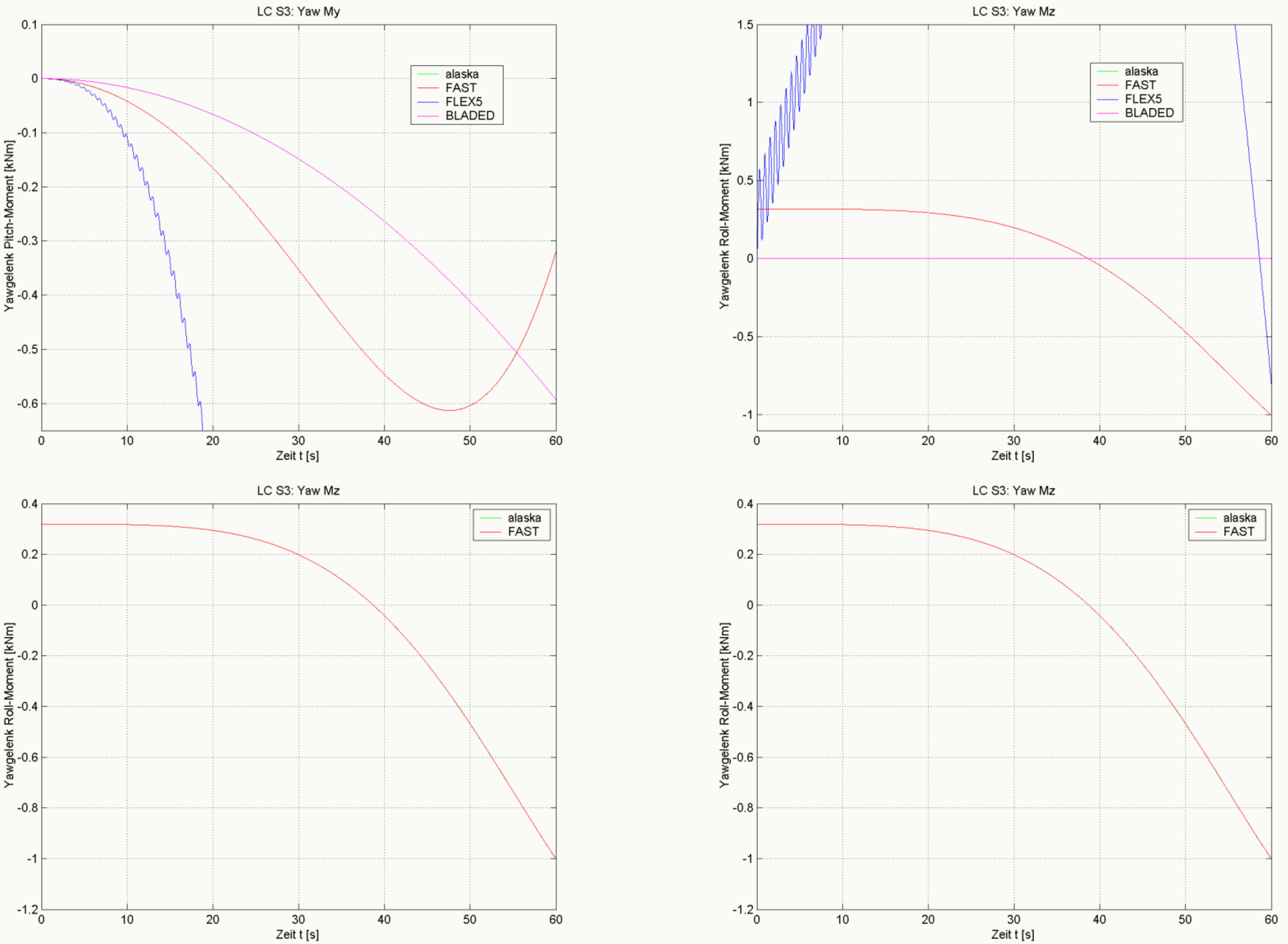
$$\dot{\varphi} = \frac{\pi}{3600} \cdot t$$

$$\ddot{\varphi} = \frac{\pi}{3600}$$

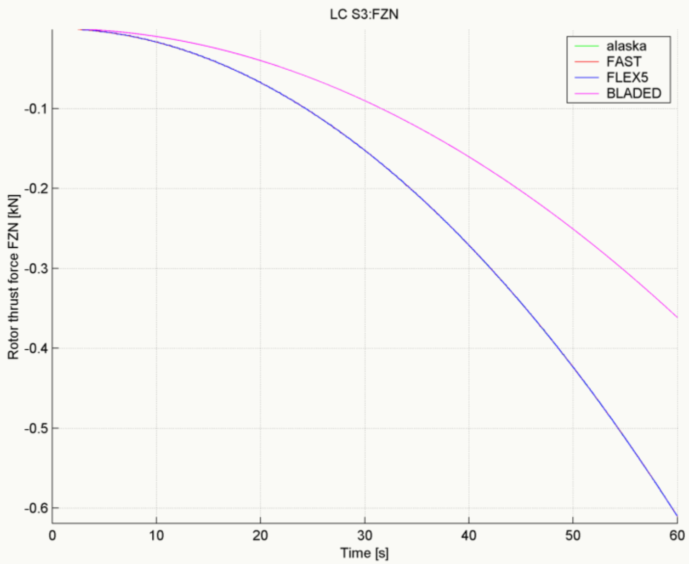


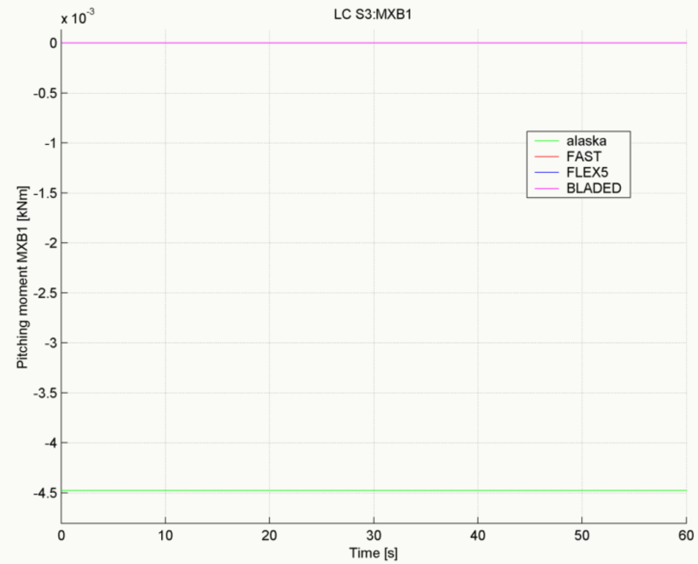
# Load Case LC_S3, Aerodynamic Forces off, Yaw Actuator velocity controled

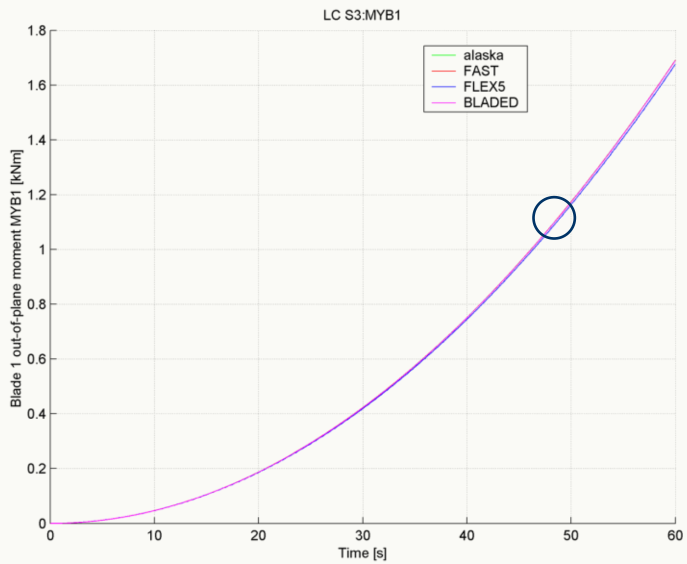


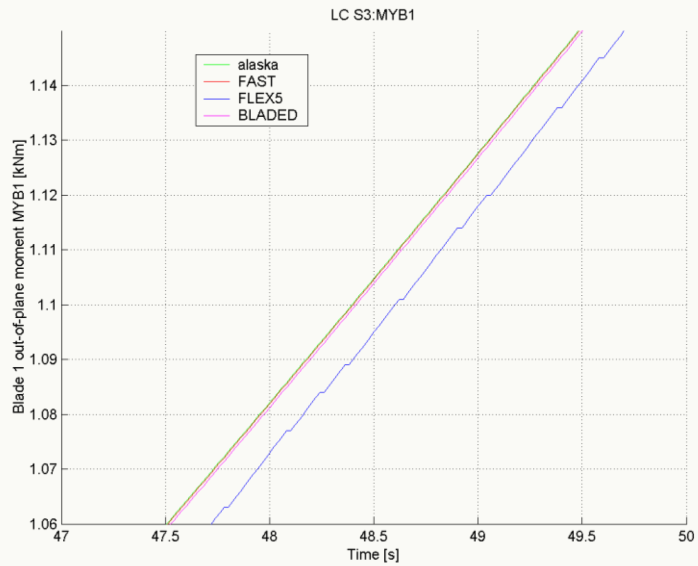


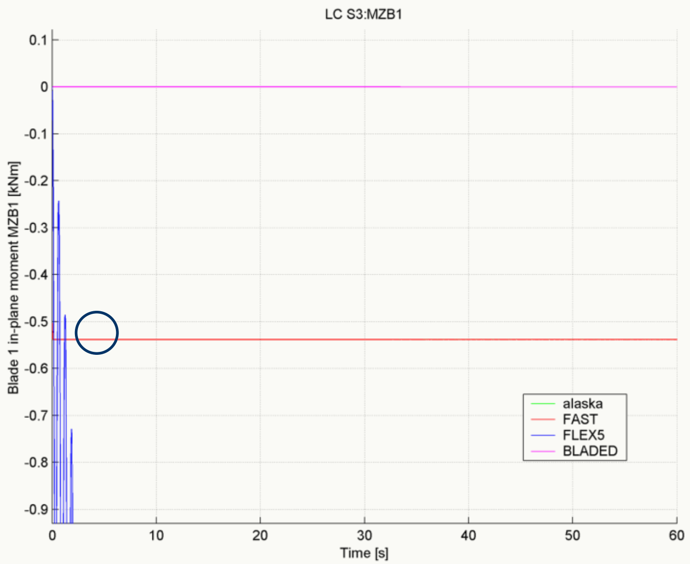
# Load Case LC_S3, Aerodynamic Forces off, Yaw Actuator velocity controled

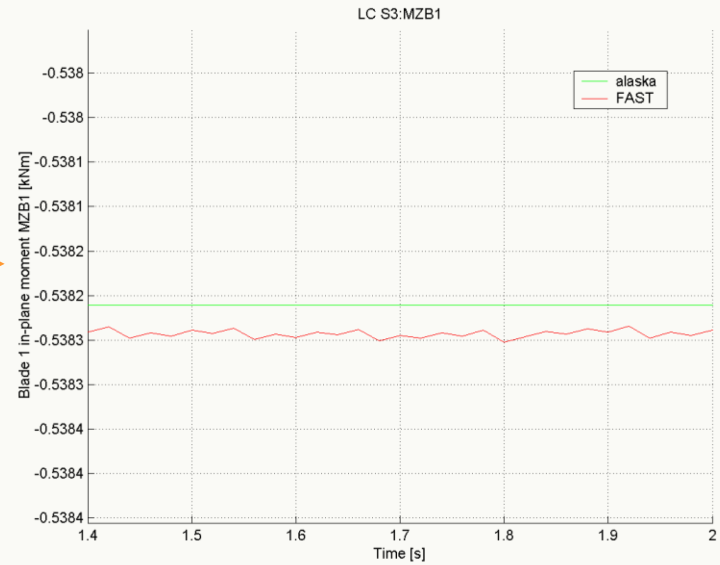



LC S3:MZB1
Blade 1 in-plane moment MZB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC S3:MZB1
Blade 1 in-plane moment MZB1 [kNm]
Time [s]
alaska
FAST

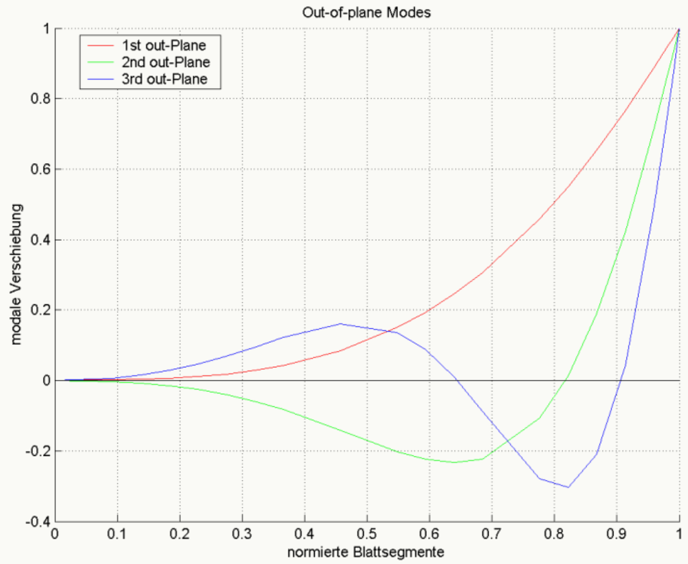
**In load case LC S4, the frequencies and mode shapes of the reference blade have been compared. All codes use a modal representation of the blade structure. A modal analysis calculation of a finite element model of the blade structure is performed at first, to compute the frequencies and mode shapes which are needed for any subsequent calculation. In all the validated codes, the finite element model of the blade structure is based on a three-dimensional beam element.**

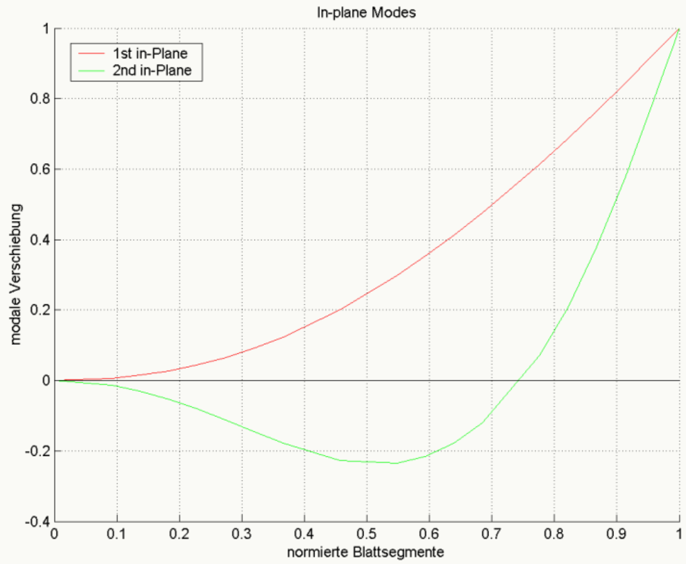
## Comparison of frequencies

- **The finite element model representation of the reference blade and the modal analysis calculation were performed by the following codes ala/Flex, BModes, FLEX5, and BLADED.**

| Mode Number | Mode Type | Frequency (Hz) | | | |
|---|---|---|---|---|---|
| | | ala/Flex | BModes | FLEX5 | BLADED |
| 1 | Out-of-plane mode | 0.7427 | 0.7427 | 0.741 | 0.743 |
| 2 | In-plane mode | 1.3505 | 1.351 | 1.3532 | 1.351 |
| 3 | Out-of-plane mode | 2.0497 | 2.0501 | 2.0385 | 2.051 |
| 4 | Out-of-plane mode | 4.3868 | 4.3884 | - | 4.39 |
| 5 | In-plane mode | 4.7927 | 4.7987 | 4.8061 | 4.8 |

## Mode shapes of the reference blade



# Load Case LC_S5, Frequencies and Mode Shapes of a Finite Element Model of the Tower Structure

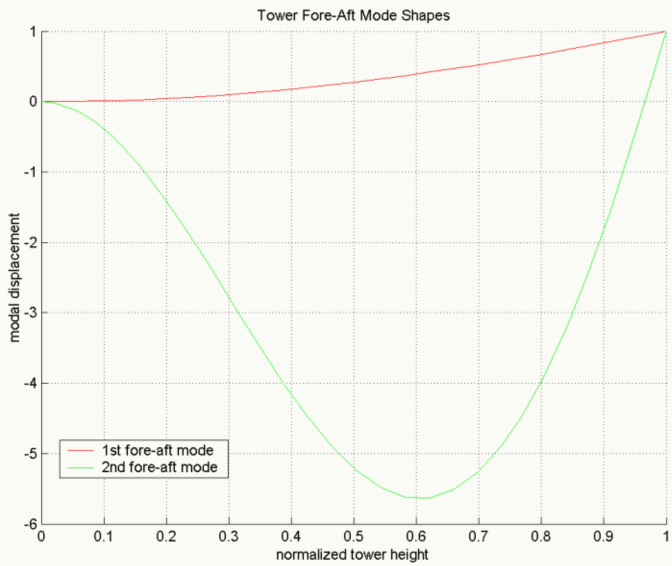
**In load case LC S5, the frequencies and mode shapes of the reference tower have been compared. All codes use a modal representation of the tower structure. A modal analysis calculation of a finite element model of the tower structure is performed at first, to compute the frequencies and mode shapes which are needed for any subsequent calculation. In all the validated codes, the finite element model of the tower structure is based on three-dimensional beam element. In BLADED, a finite element model of the complete wind turbine will be used for the modal analysis. This model is more detailed than a model with a tower and a tower-top mass as used in ala/FLEX, BModes, and FLEX5. Therefore, some deviations in higher frequencies occur.**

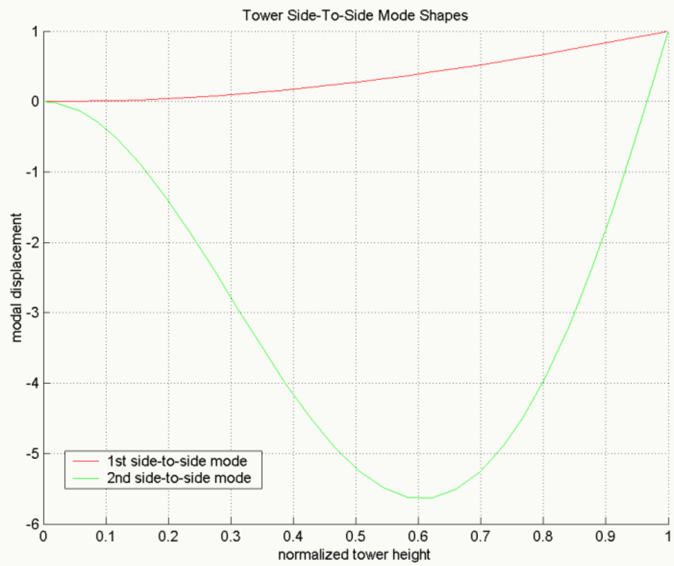
## Comparison of frequencies

- **The finite element model representation of the reference tower and the modal analysis calculation were performed by the codes ala/Flex, BModes, FLEX5, and BLADED.**

| Mode Number | Mode Type | Frequency (Hz) | | | |
|---|---|---|---|---|---|
| | | ala/Flex | BModes | FLEX5 | BLADED |
| 1 | fore-aft mode | 0.377 | 0.377 | 0.366 | 0.369 |
| 2 | side-to-side mode | 0.377 | 0.377 | 0.366 | 0.366 |
| 3 | fore-aft mode | 3.375 | 3.384 | 3.119 | 2.467 |
| 4 | side-to-side mode | 3.375 | 3.384 | 3.119 | 2.12 |

## Mode shapes of the reference tower



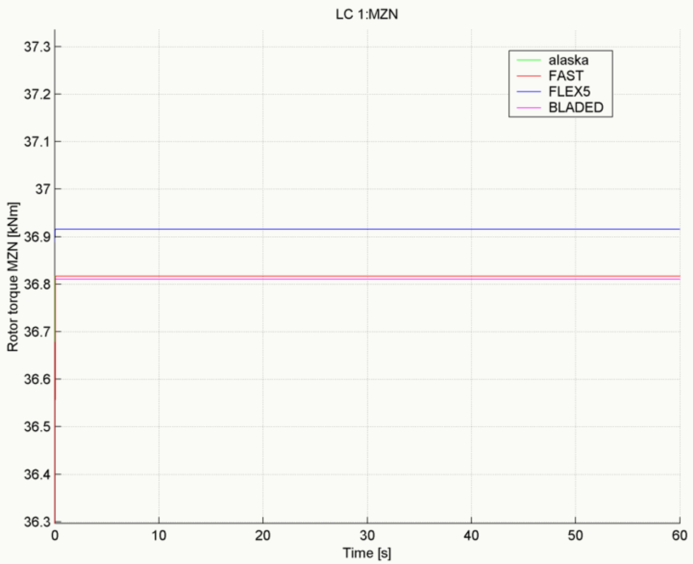
# Definition of Load Cases – LCGroup I

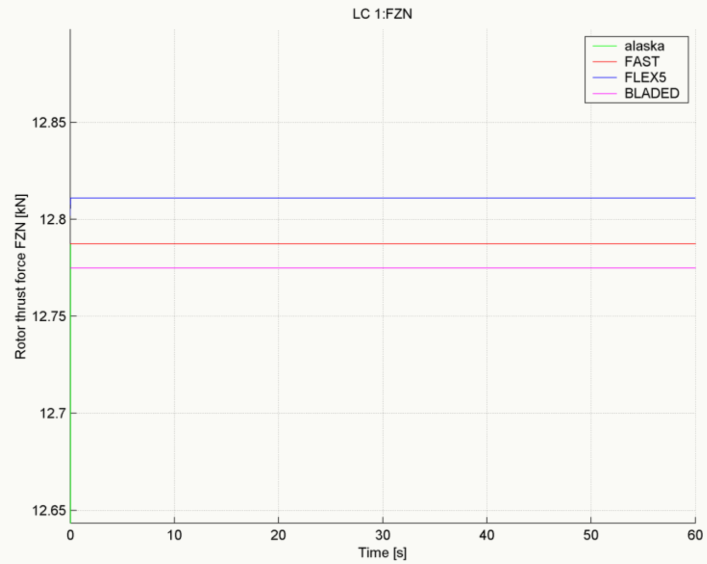
## LCGroup I

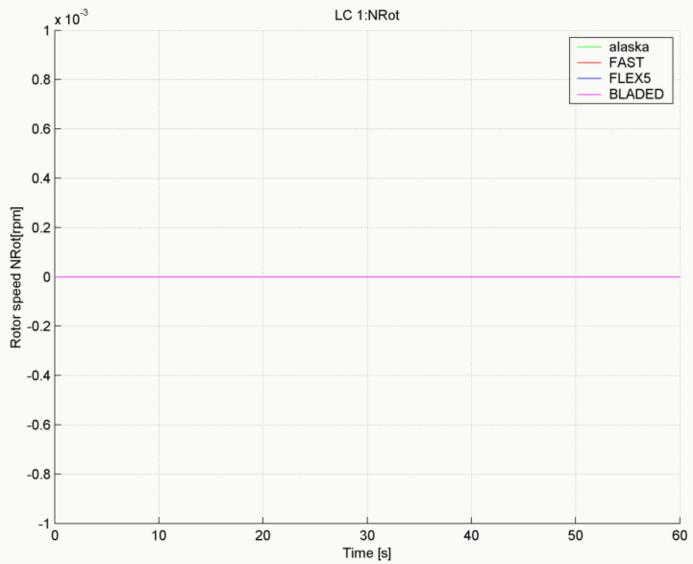
| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Pitch | Yaw | Rotor IC | Generator / Motor | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | EqI/GDW | None/Bed/Oye | on/off | on/off | None/Log/Exp | [s] | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | const/var [m/s] | const/var | [on/off] | [s] | [s] |
| 1 | EqI | None | on | off | None | 0.02 | off | off | fixed, 0° | fixed, 0° | 0 | off | 8 | 0° | off | 0,02 | 60 |
| 3 | EqI | None | on | off | None | 0.02 | off | off | fixed, 0° | fixed, 0° | 0 | off | var 1 | 0° | off | 0,02 | 100 |
| 4 | EqI | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 0 | off | var 1 | 0° | off | 0,02 | 300 |
| 5 | EqI | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 0 | off | 8 | 0° | off | 0,02 | 300 |
| 7 | EqI | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 8 | off | var 3 | 0° | off | 0,02 | 500 |
| 8 | EqI | None | on | off | None | 0.02 | off | on | fixed, 10° | fixed, 0° | 8 | off | var 4 | 0° | off | 0,02 | 350 |

- **wind shear off**
- **tower shadow off**
- **rigid turbine model**

**The load case group LCGroup I defines test scenarios for the validation of the aerodynamic loads. In load case 1 a parked turbine has been simulated to validate the aerodynamic forces without the influence of the rotor rotation. The load cases 4 to 8 simulate the speed up of a rigid turbine model under different wind and model conditions. The generator is switched off, so the rotor will accelerate without an external load.**

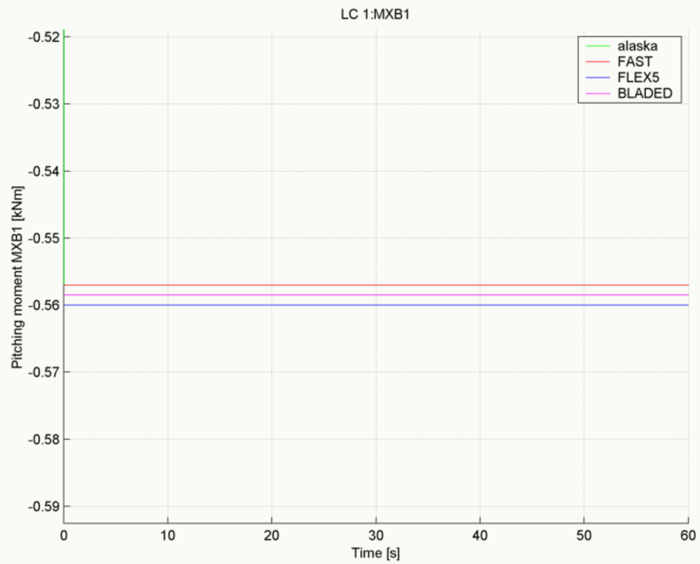

LC 1:MZN
Rotor torque MZN [kNm]
37.3
37.2
37.1
37
36.9
36.8
36.7
36.6
36.5
36.4
36.3
0
10
20
30
40
50
60
Time [s]
alaska
FAST
FLEX5
BLADED

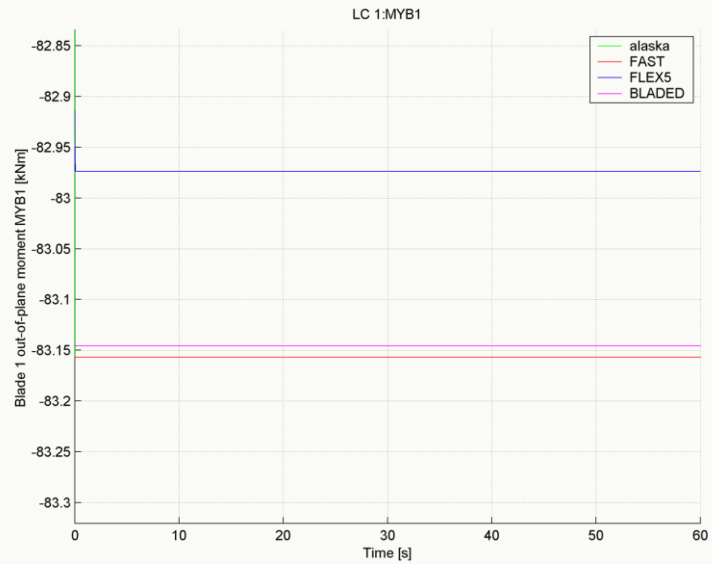

LC 1:FZN
Rotor thrust force FZN [kN]
12.85
12.8
12.75
12.7
12.65
0
10
20
30
40
50
60
Time [s]
alaska
FAST
FLEX5
BLADED

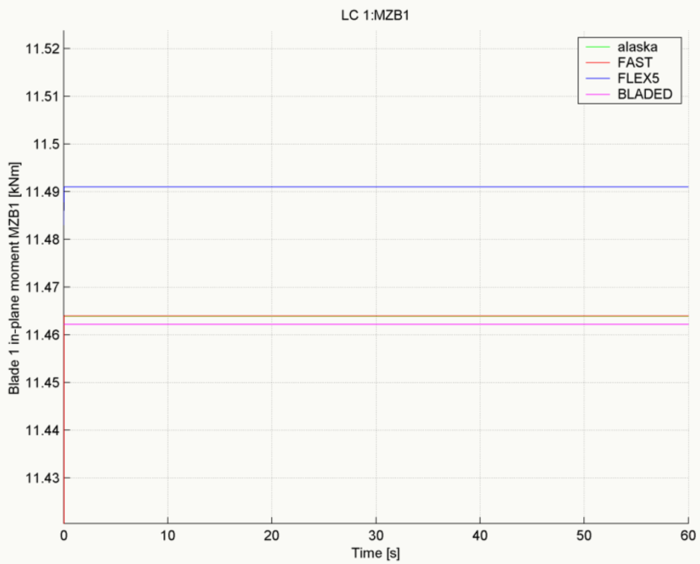

LC 1:NRot
x 10^-3
Rotor speed NRot[rpm]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
10
20
30
40
50
60
Time [s]
alaska
FAST
FLEX5
BLADED

# Load Case LC 1, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°





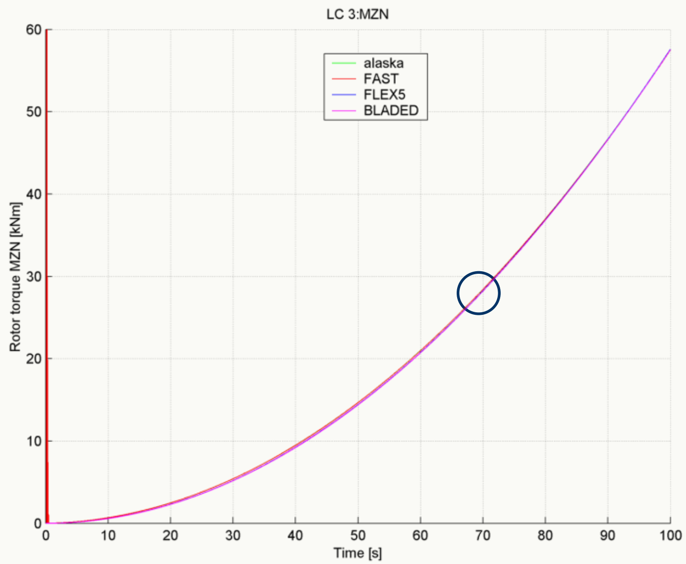



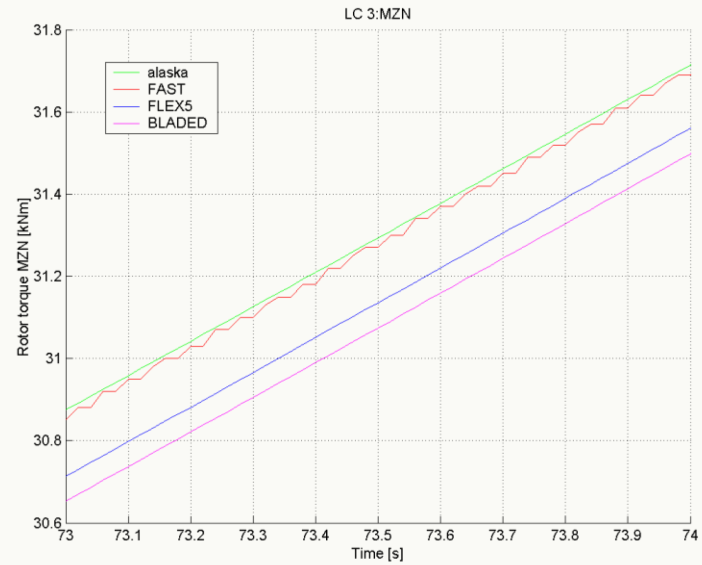



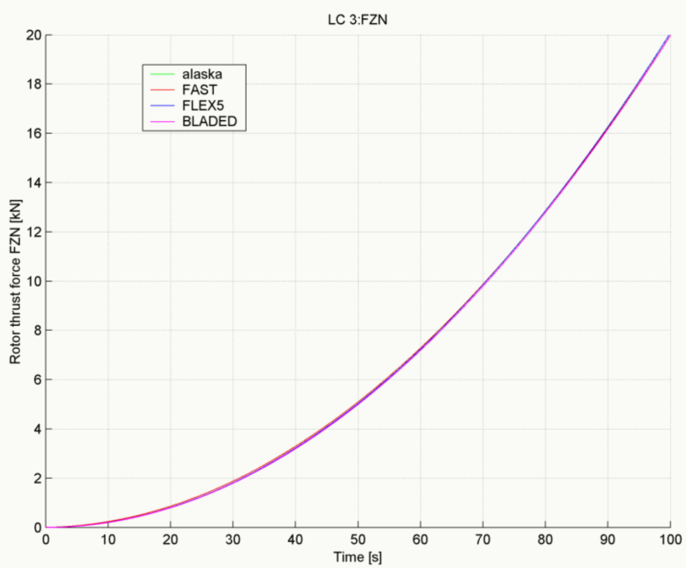

- **results with a  very good agreement**
- **a validated aerodynamic blade model for a fixed rotor**

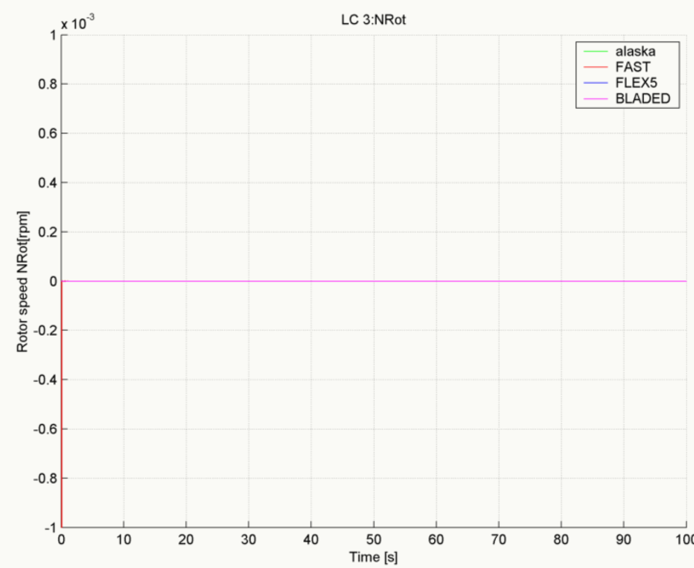
# Load Case LC 3, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°



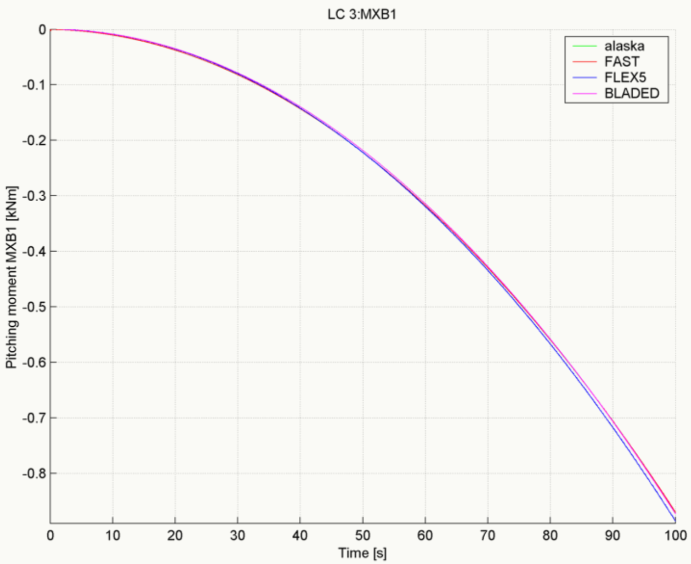


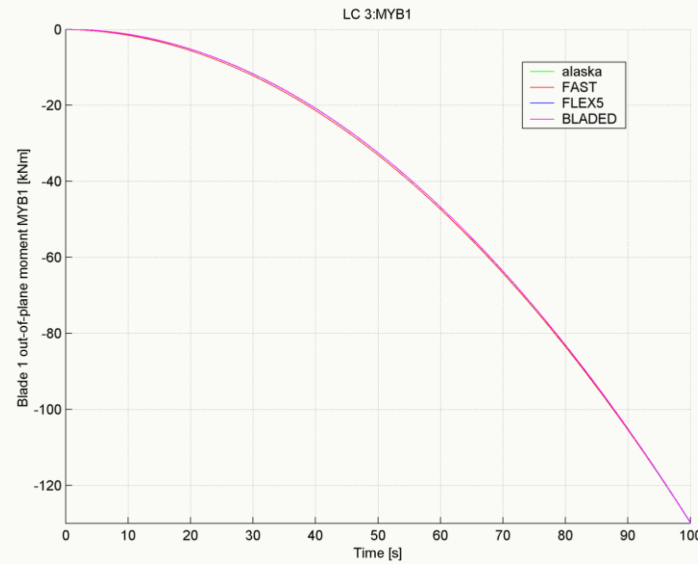



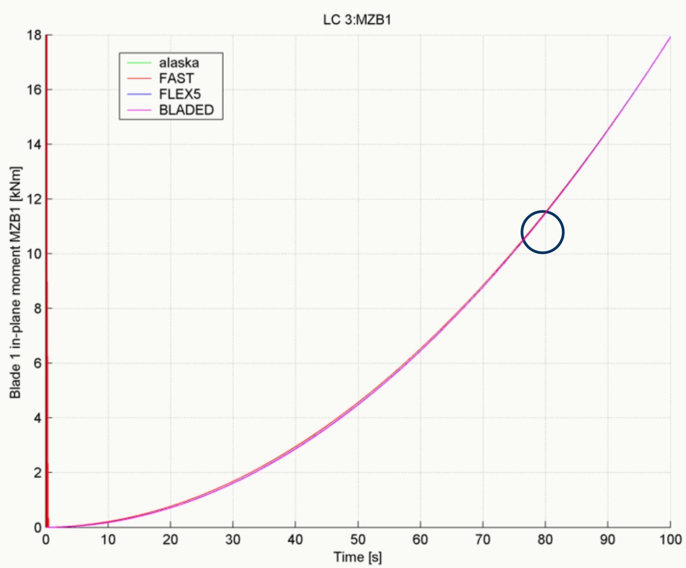



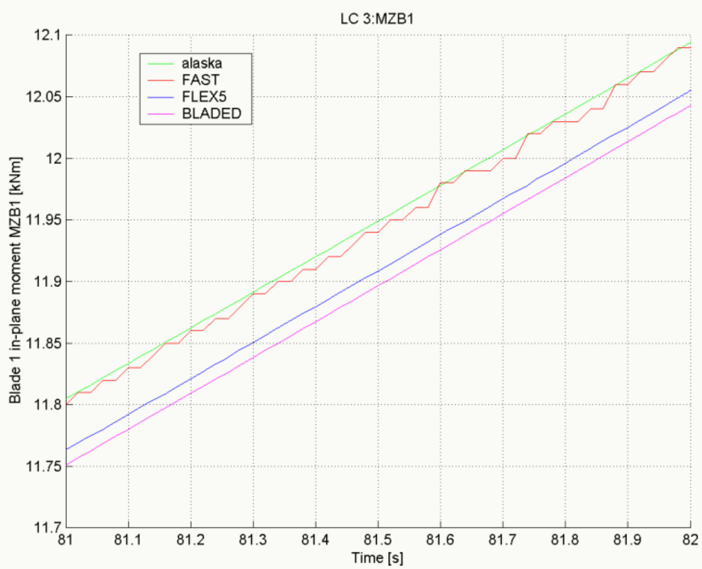



# Load Case LC 3, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°

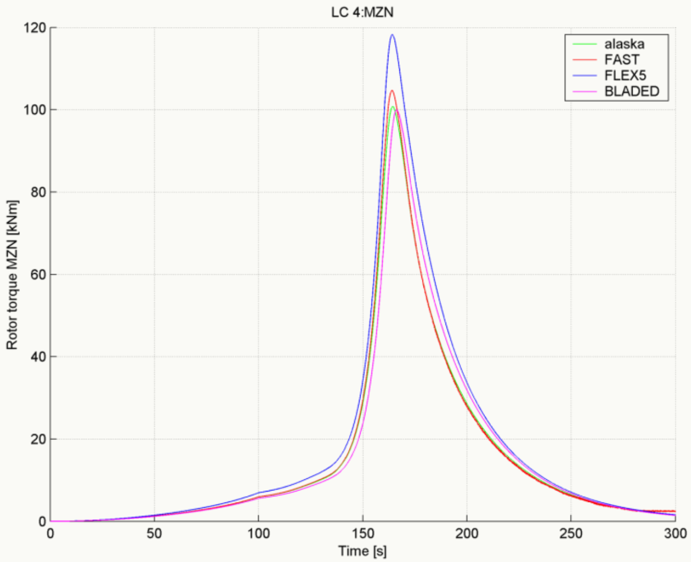


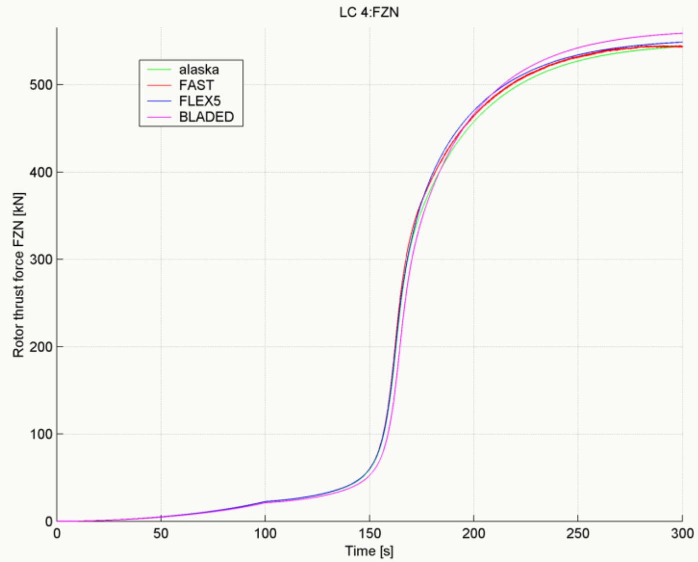



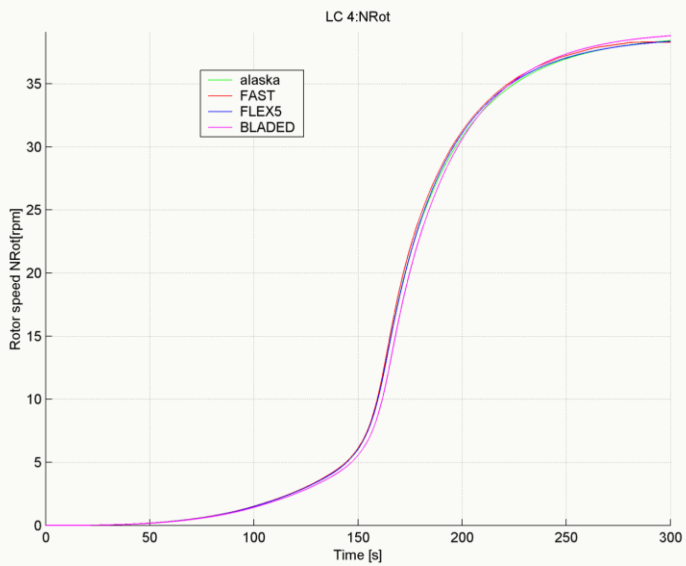



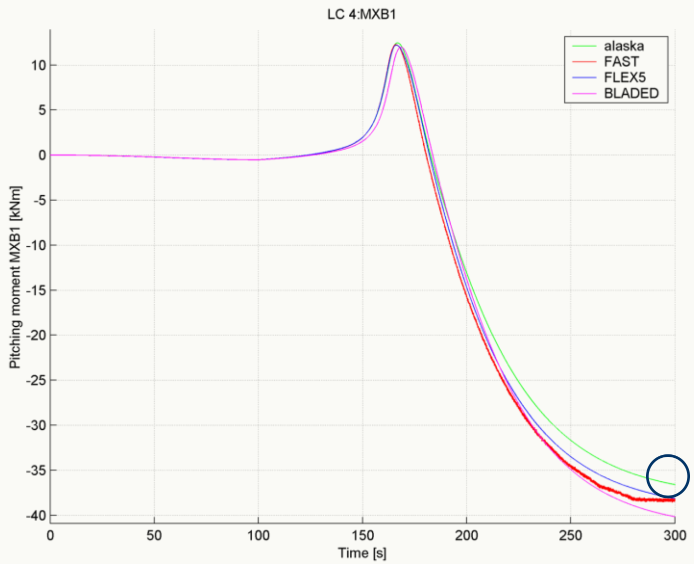
# Load Case LC 4, var. Wind, Pitch fixed 0°, Yaw fixed 0°

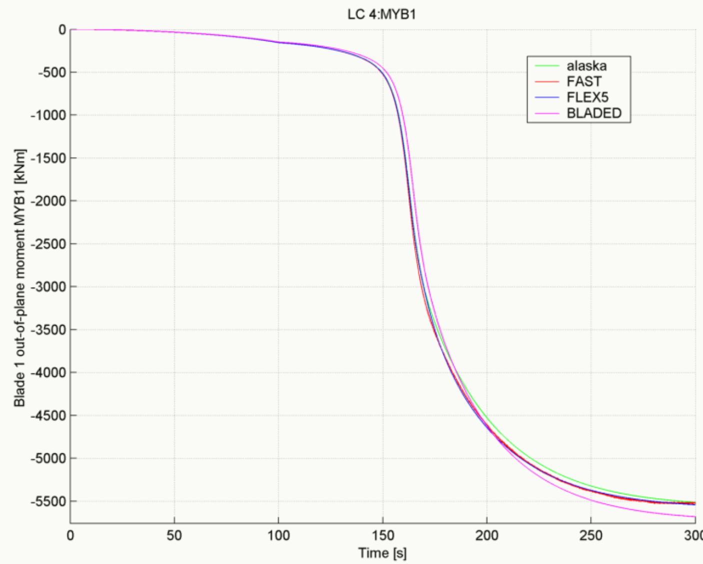


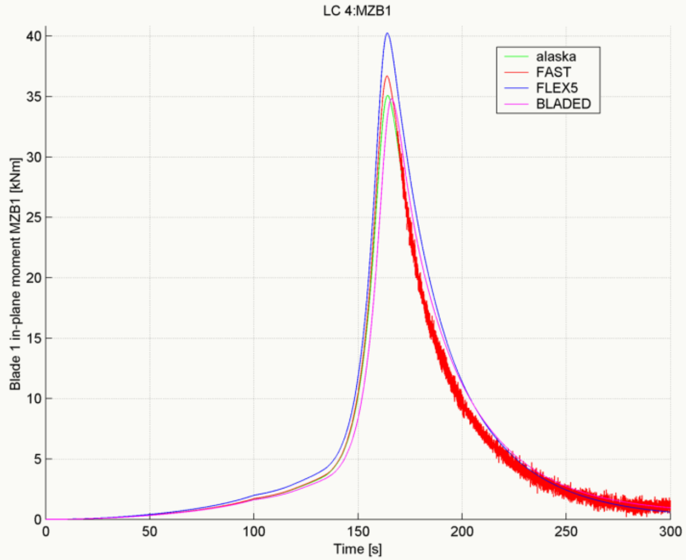



# Load Case LC 4, var. Wind, Pitch fixed 0°, Yaw fixed 0°

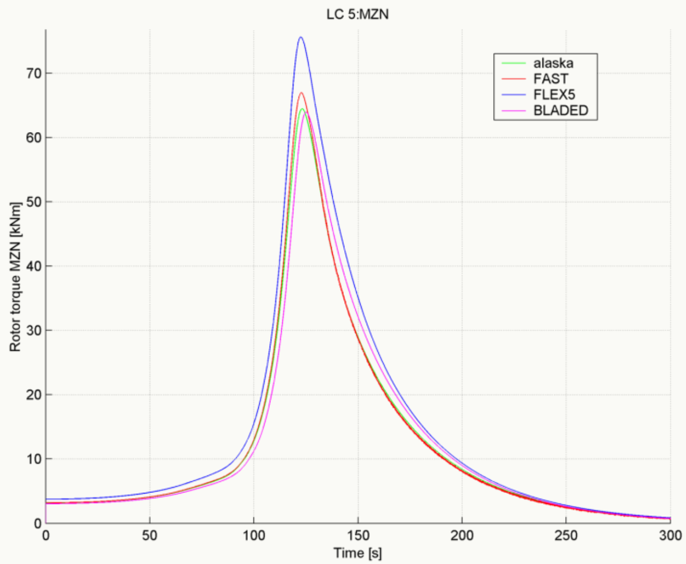


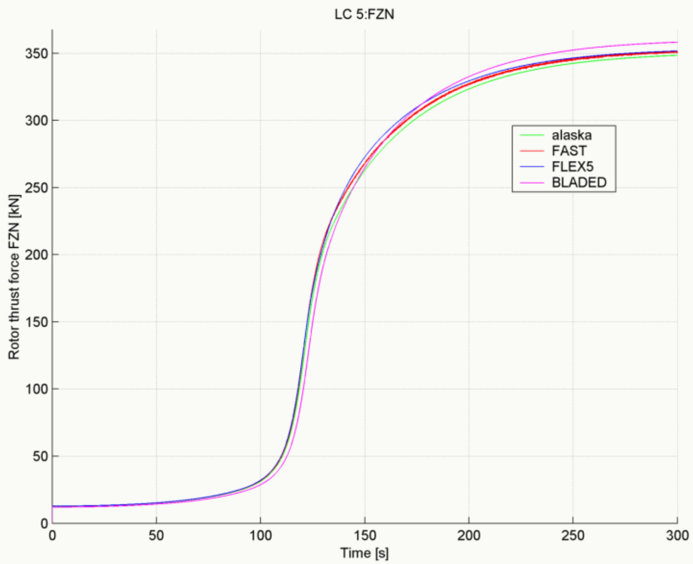



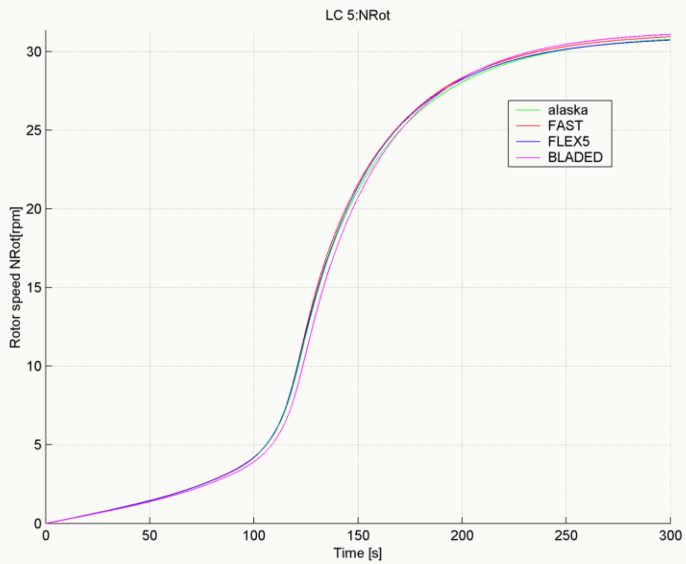




- **with an increase in the rotor speed the deviation in the pitching moment increases in alaska/Wind**
  - **this is caused by the missing moments of deviation for the rotor blades in BLADED, FAST, and FLEX5 (load case LC S1)**
- **at the point of maximum power, the FLEX5 curve is superelevated**

# Load Case LC 5, const. Wind = 8 m/s, Pitch fixed 0°, Yaw fixed 0°



# Load Case LC 5, const. Wind = 8 m/s, Pitch fixed 0°, Yaw fixed 0°

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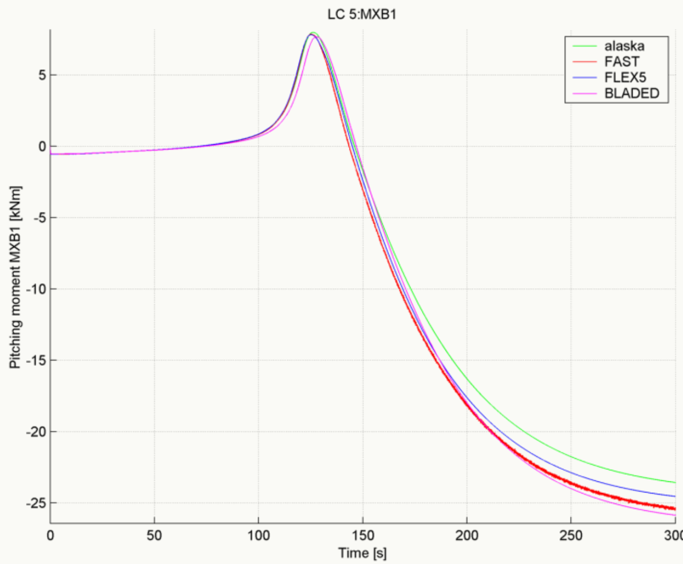
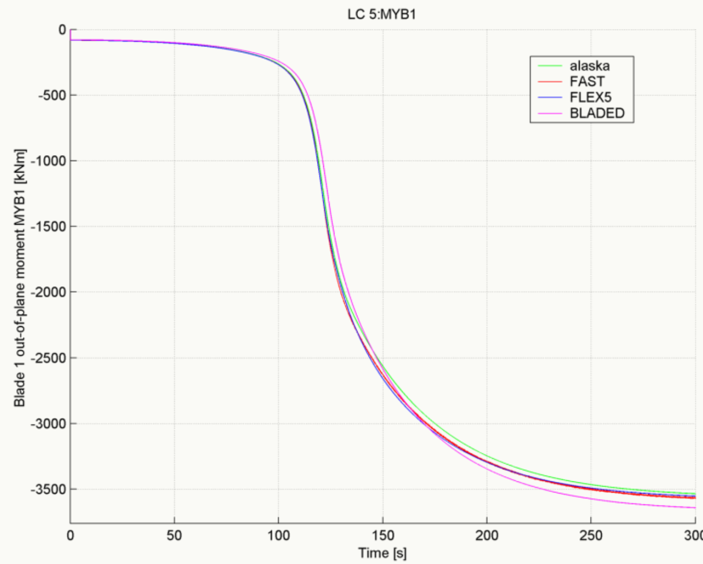
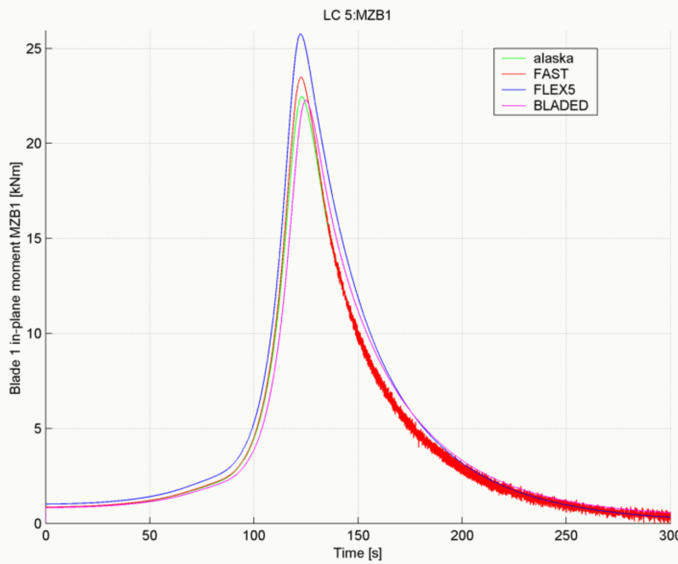
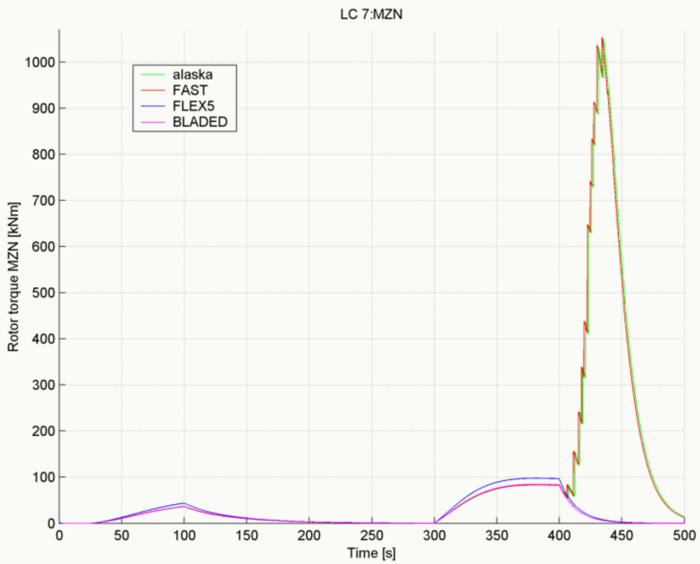
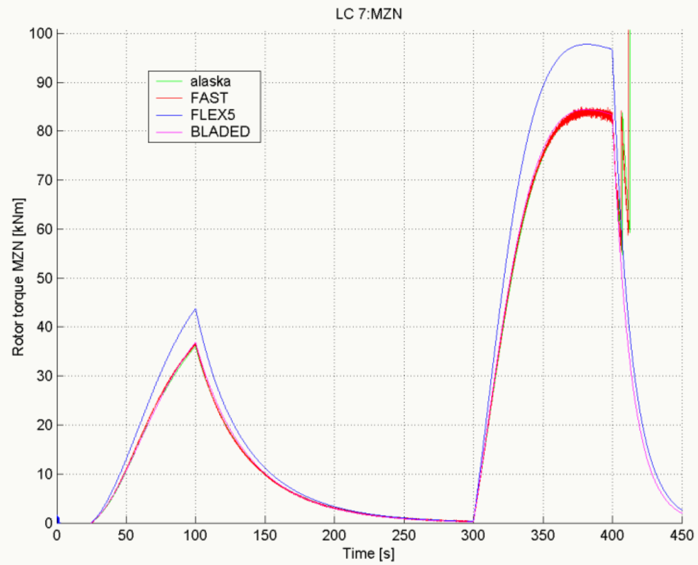
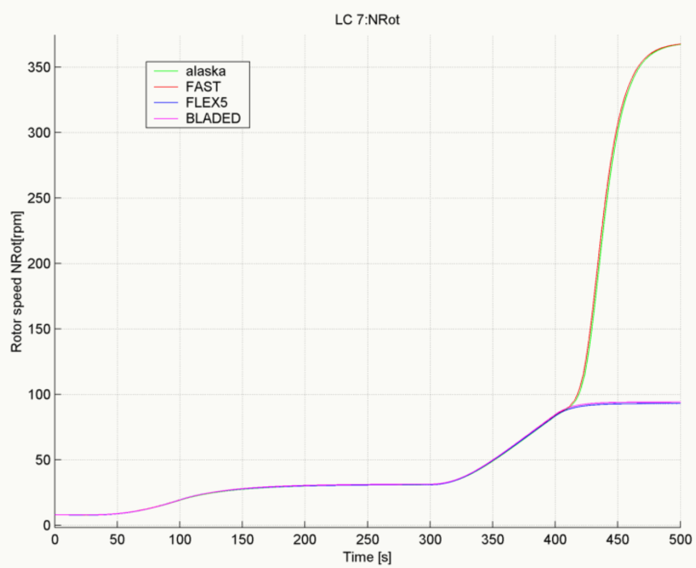


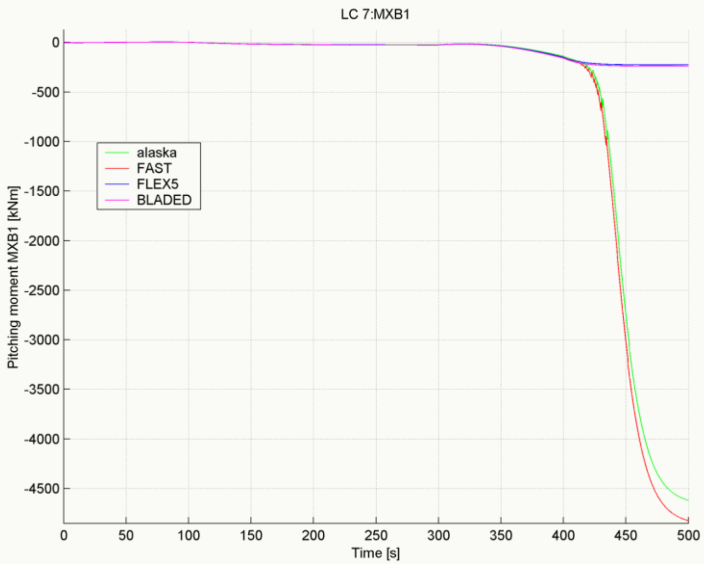


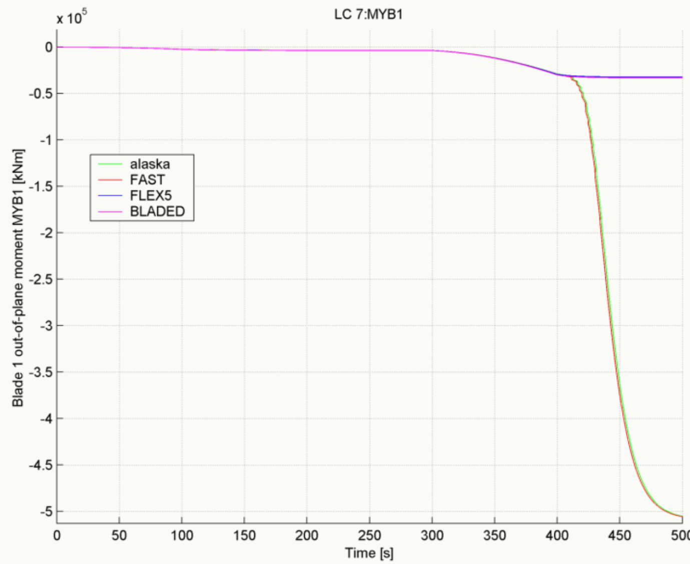



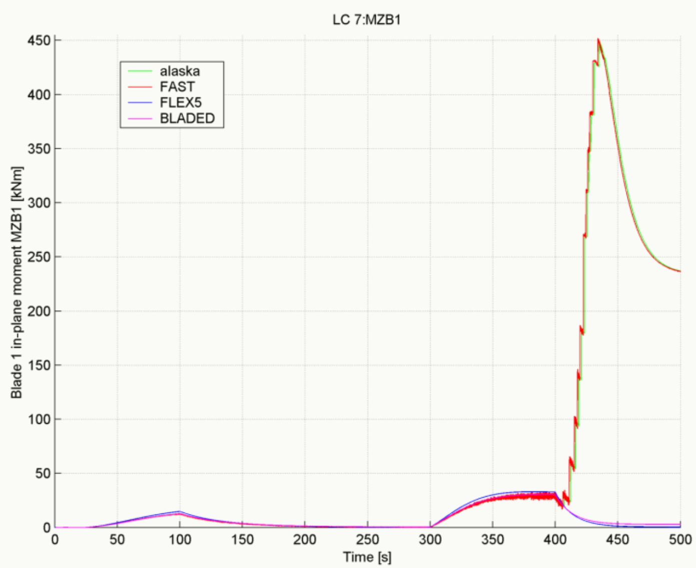




- **good agreement in normal operating range**
- **reaching the validity limits of the aerodynamic model, a different behaviour occurs**

# Load Case LC 7, var. Wind, Pitch fixed 0°, Yaw fixed 0°

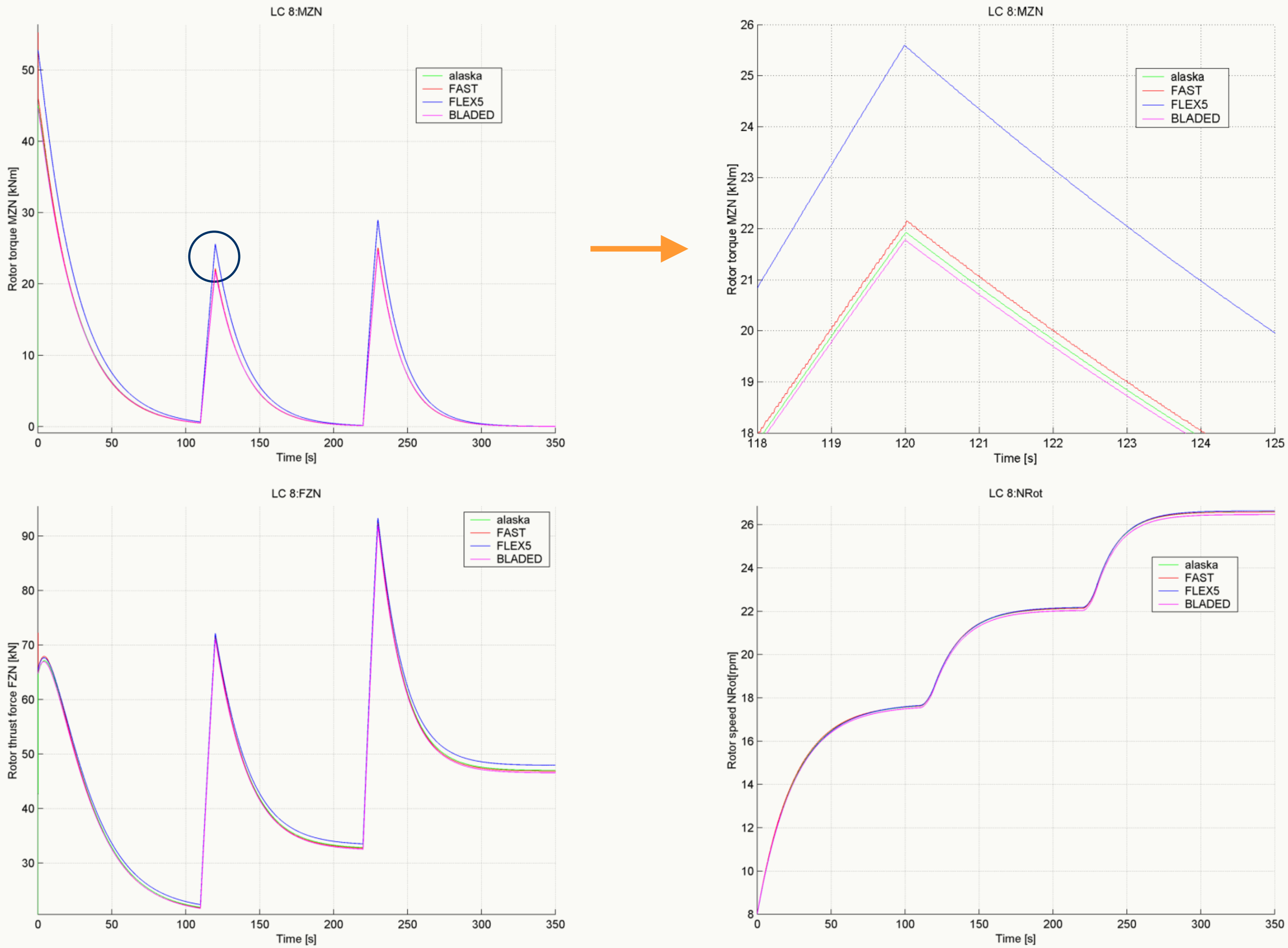


# Load Case LC 8, var. Wind, Pitch fixed 10°, Yaw fixed 0°





# Load Case LC 8, var. Wind, Pitch fixed 10°, Yaw fixed 0°

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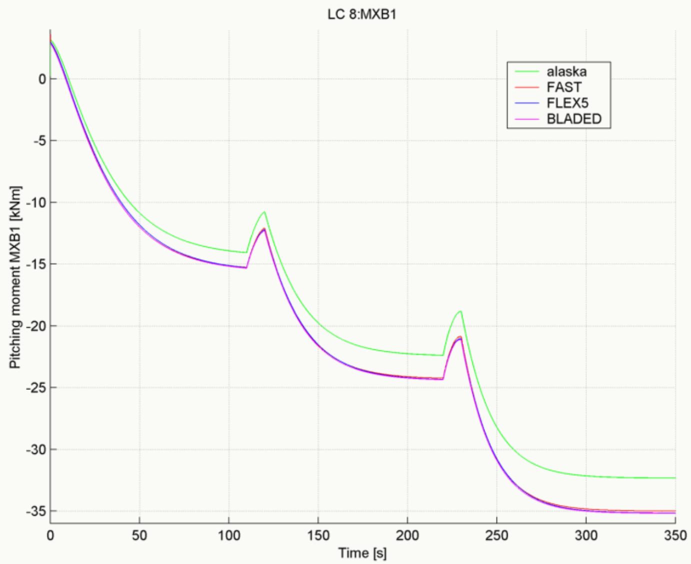


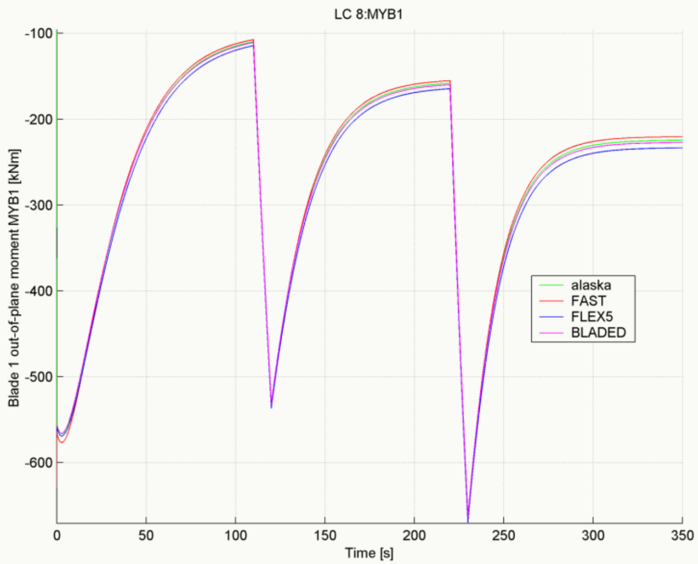


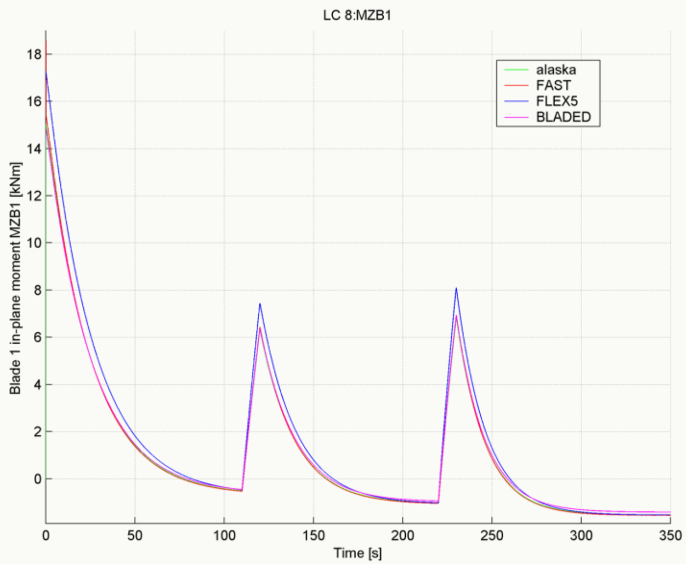

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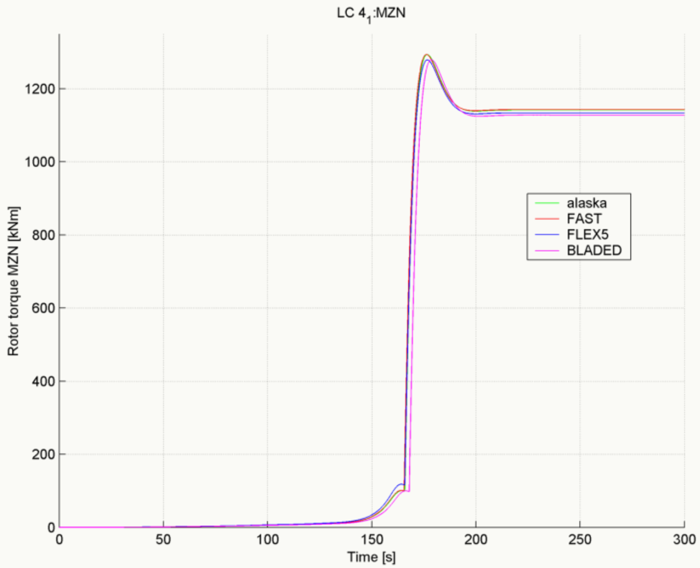
## LCGroup II

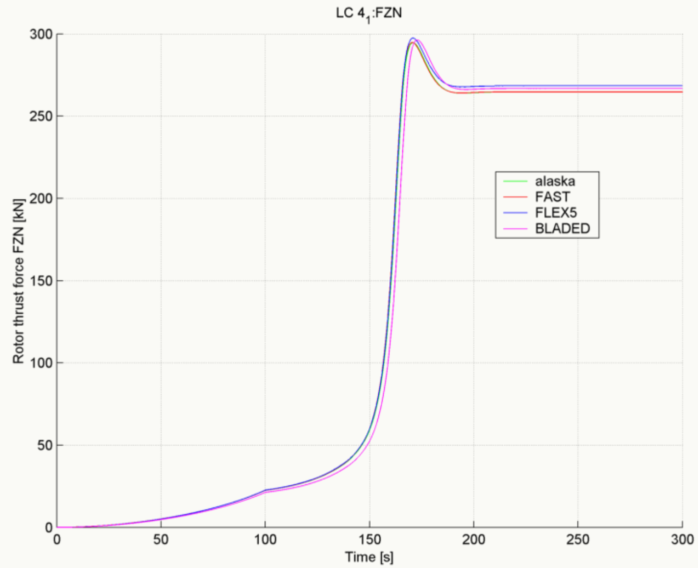
| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Pitch | Yaw | Rotor IC | Generator / Motor | Demanded Rotor Speed | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | EqI/ GDW | None/ Bed/Oye | on/off | on/off | None/Log/Exp | [s] | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | [rpm] | const/var [m/s] | const/var | [on/off] | [s] | [s] |
| 4_1 | EqI | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 0 | on | 15 | var 1 | 0° | off | 0,02 | 300 |
| 5_1 | EqI | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 0 | on | 15 | 8 | 0° | off | 0,02 | 300 |
| 7_1 | EqI | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 8 | on | 15 | var 3 | 0° | off | 0,02 | 500 |
| 8_1 | EqI | None | on | off | None | 0.02 | off | on | fixed, 10° | fixed, 0° | 8 | on | 15 | var 4 | 0° | off | 0,02 | 350 |

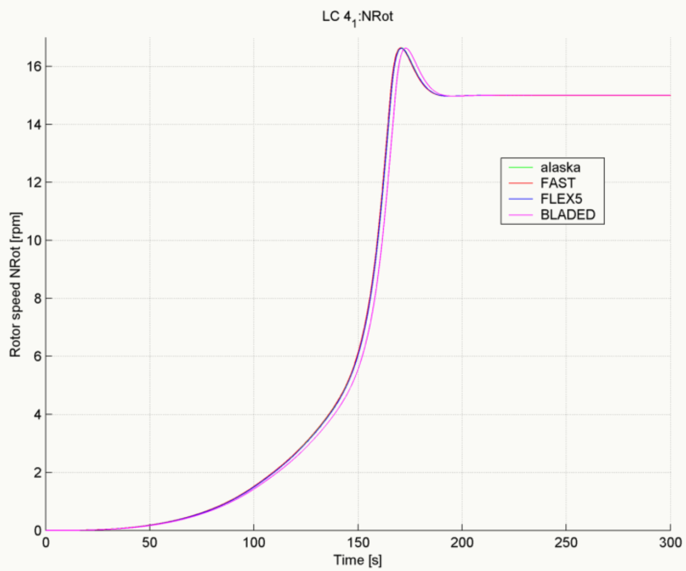
- **wind shear off**
- **tower shadow off**
- **rigid turbine model**
- **stationary rotor speed**

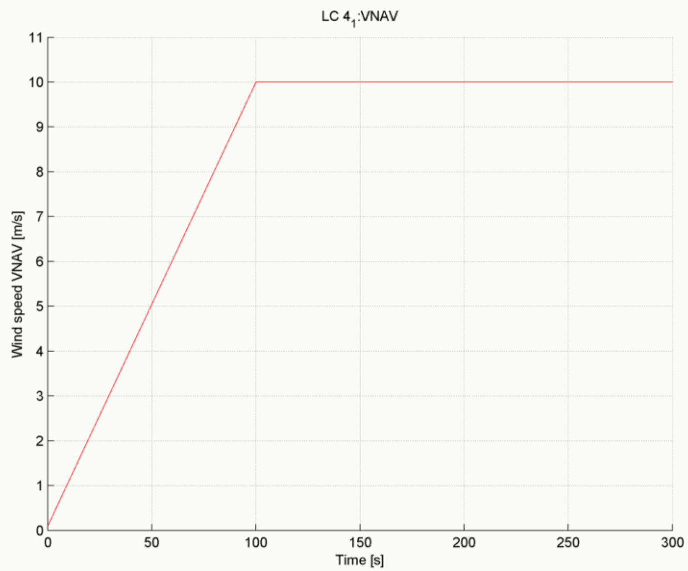
**In LCGroup II the load cases 4 to 8 of LCGroup I has been repeated with a stationary rotor speed. The rotor has been accelerated up to the predefined rotor speed and then has been kept constantly by a PI speed controller. The PI controller worked like a motor and produced an equivalent reaction torque of the aerodynamic moment of the rotor.**

# Load Case LC 4_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°

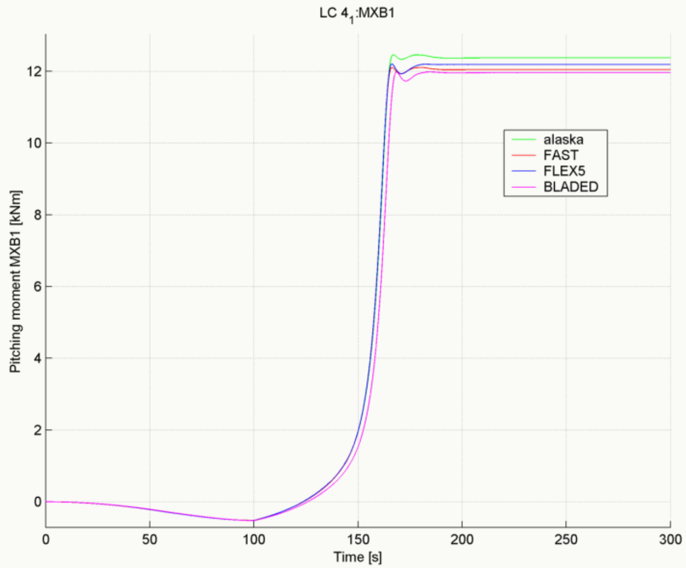


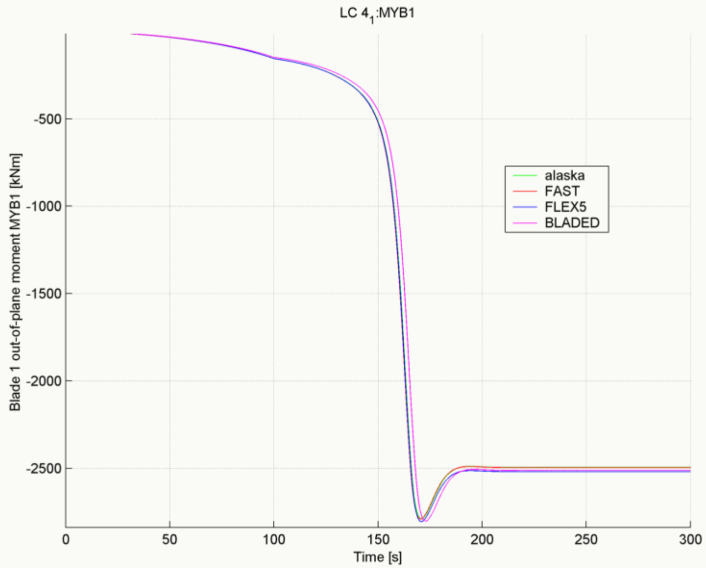



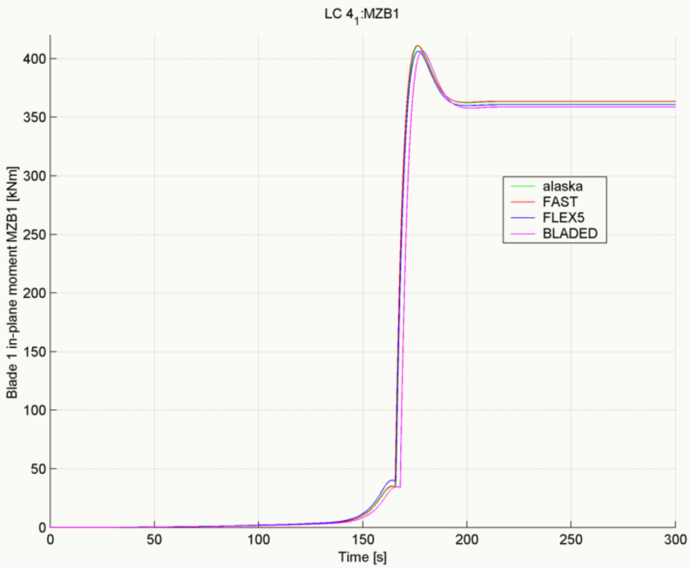



# Load Case LC 4_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°



# Load Case LC 5_1, const. Wind = 8 m/s, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°

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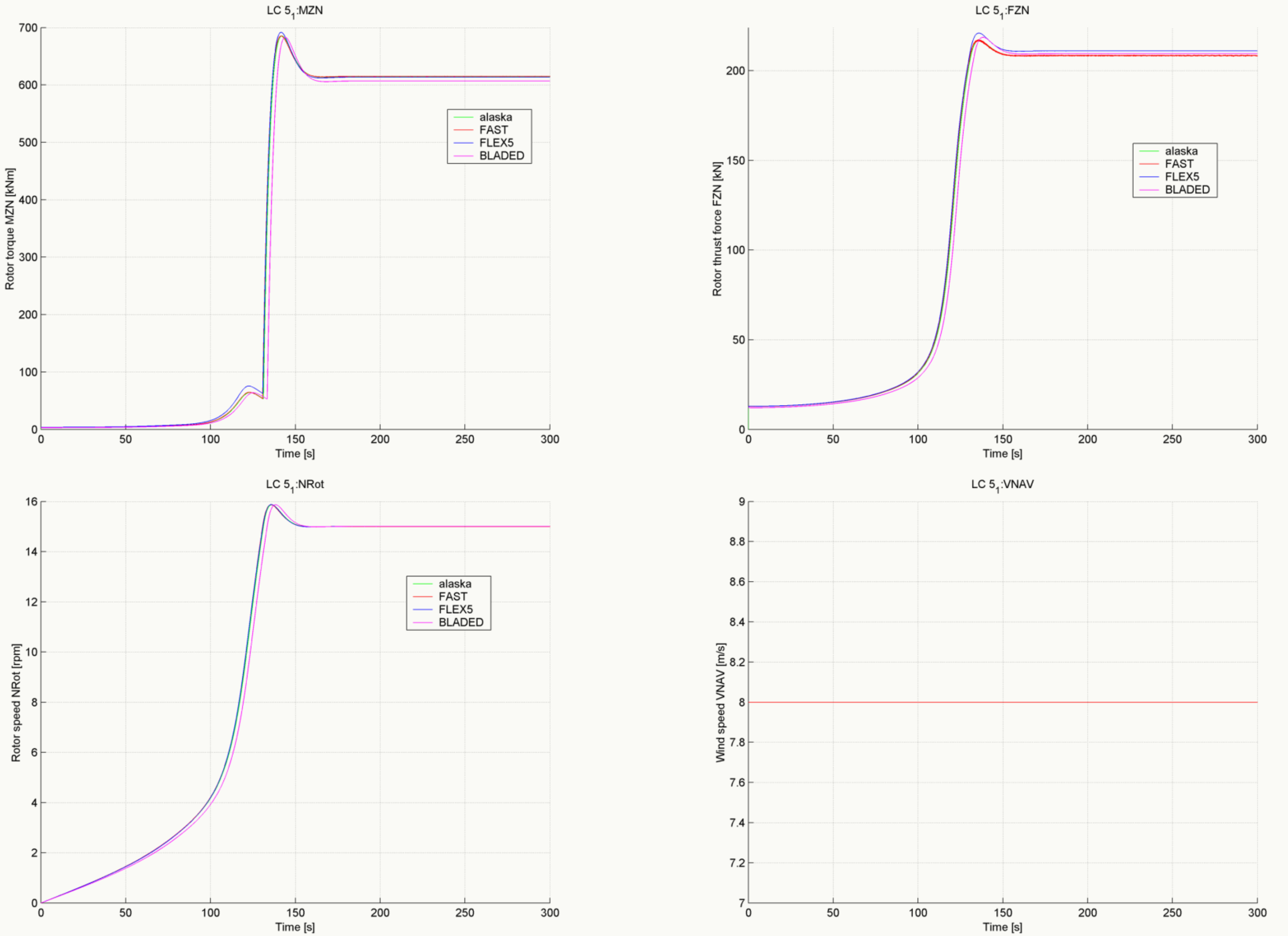
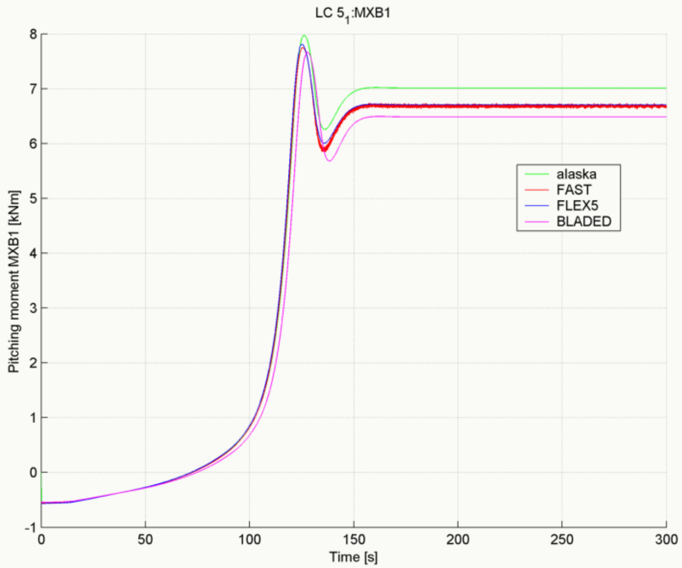
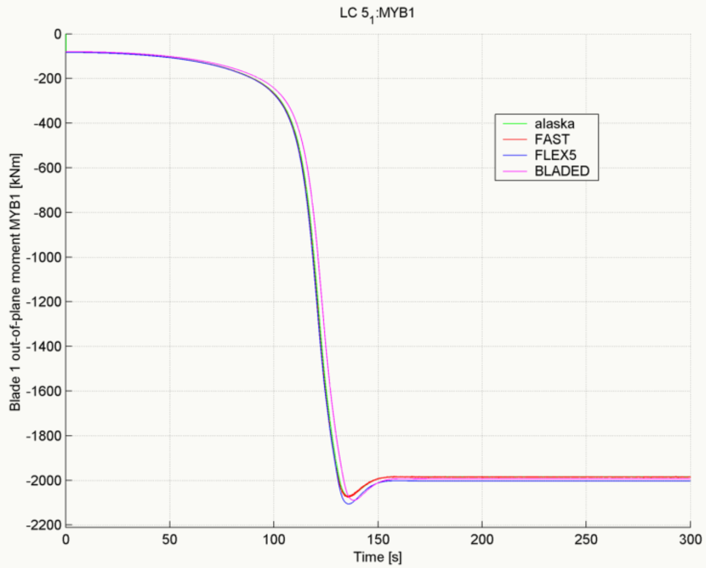
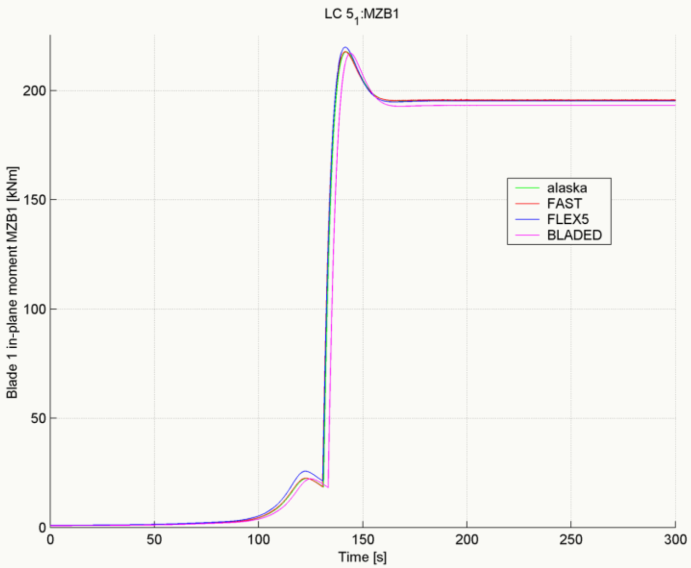


# Load Case LC 5_1, const. Wind = 8 m/s, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°



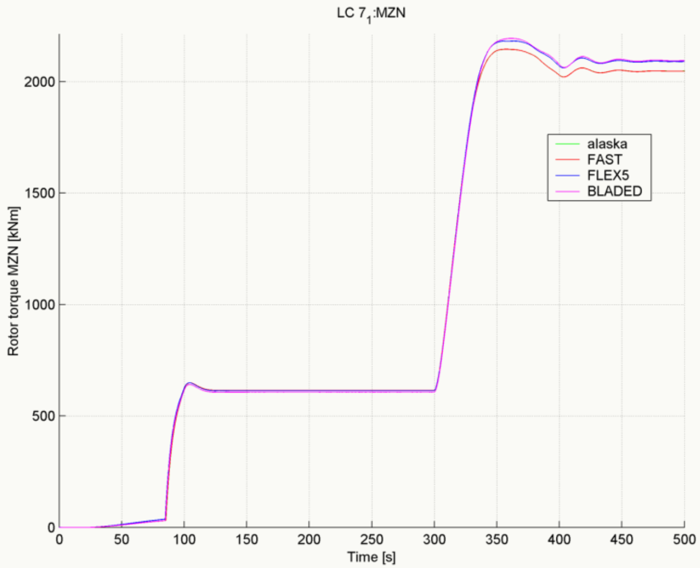


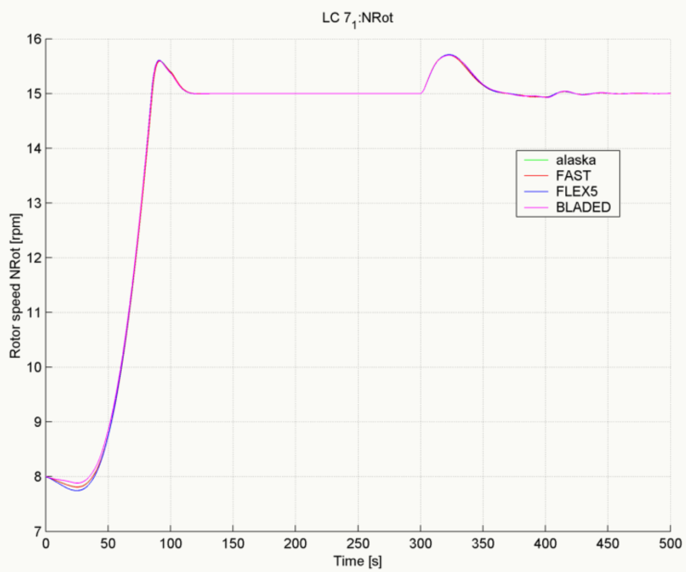



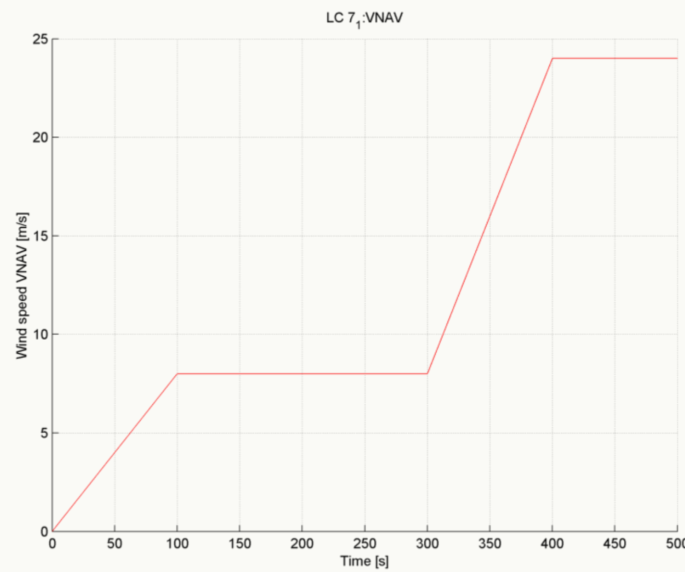
# Load Case LC 7_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°



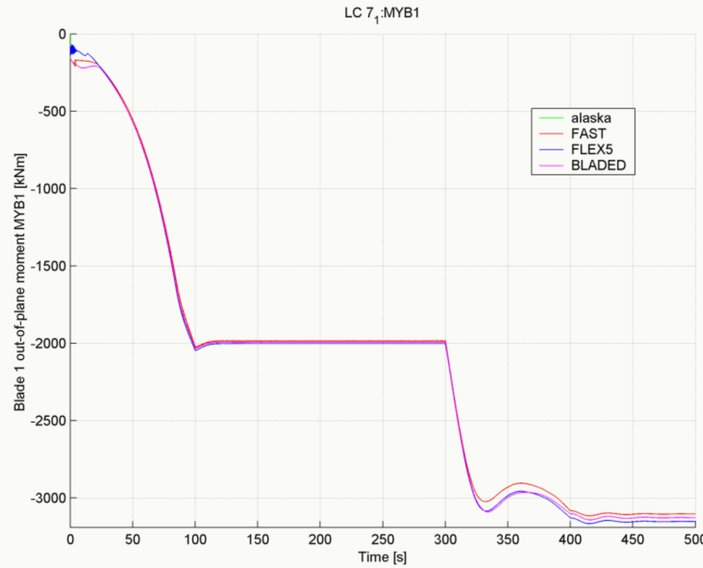


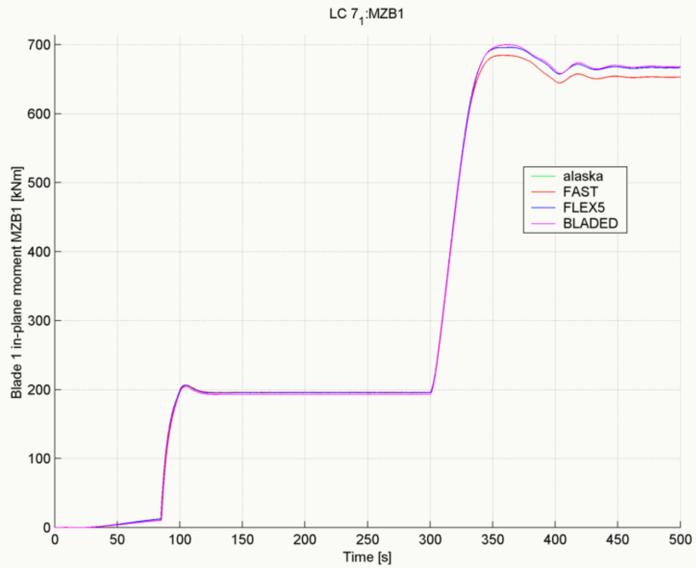




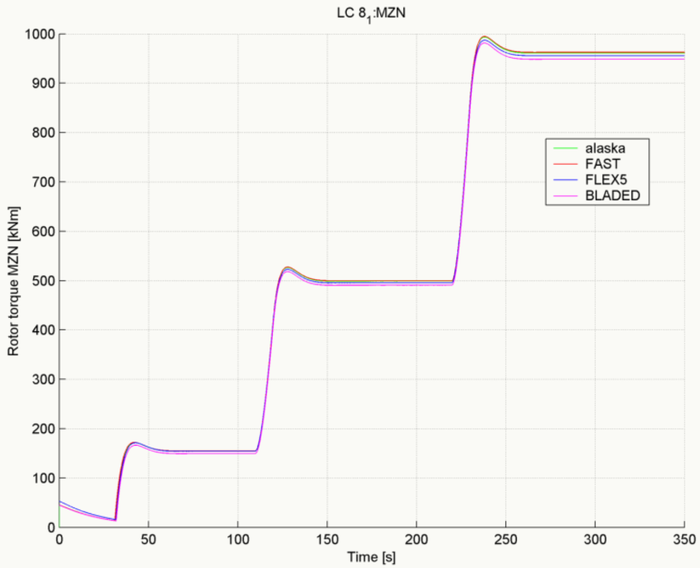
# Load Case LC 7_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°

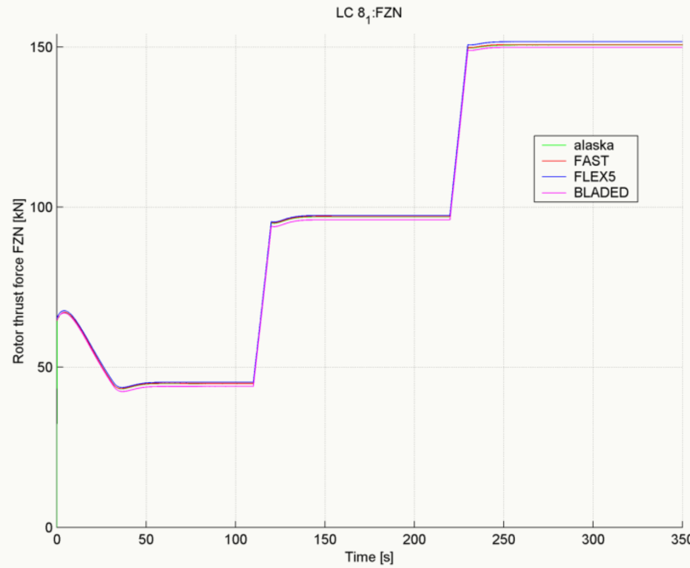



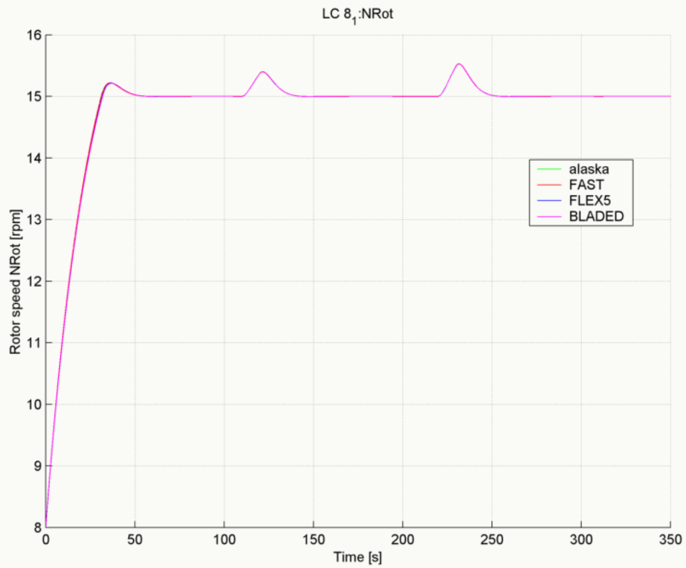



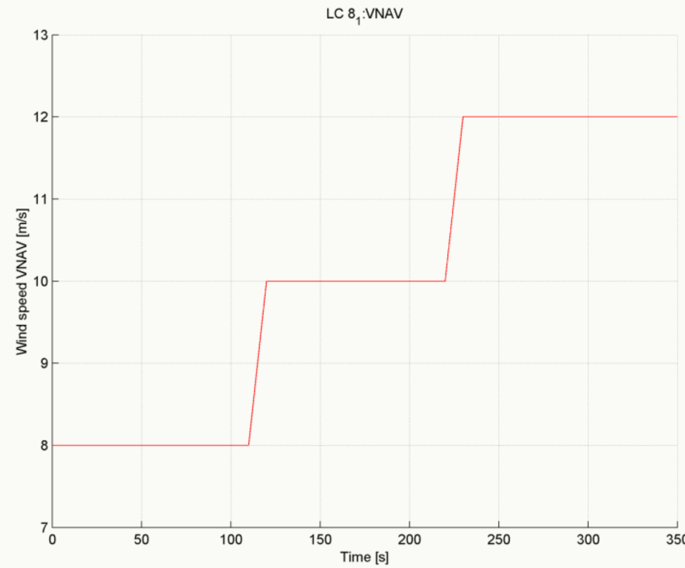
# Load Case LC 8_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 10°, Yaw fixed 0°





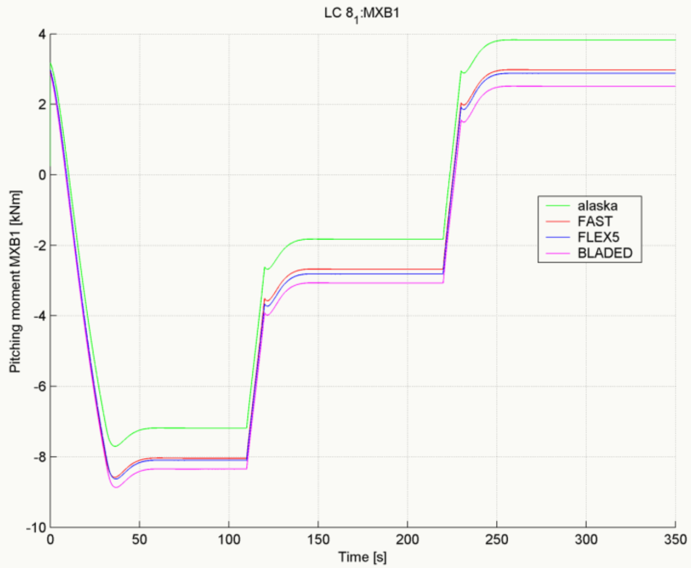



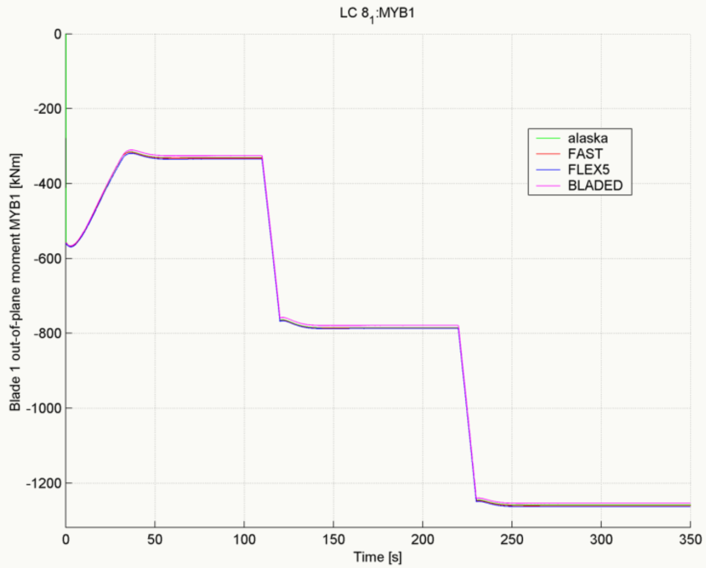



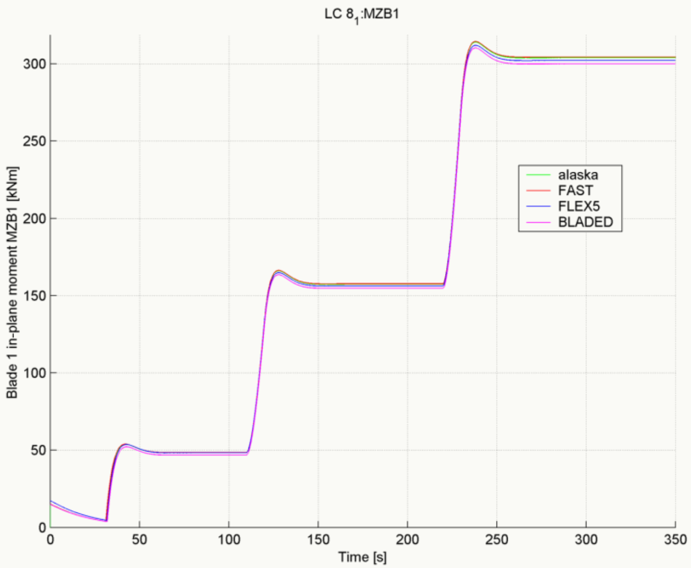



# Load Case LC 8_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 10°, Yaw fixed 0°





# Definition of Load Cases – LCGroup III

## LCGroup III
## Skewed Wake Correction

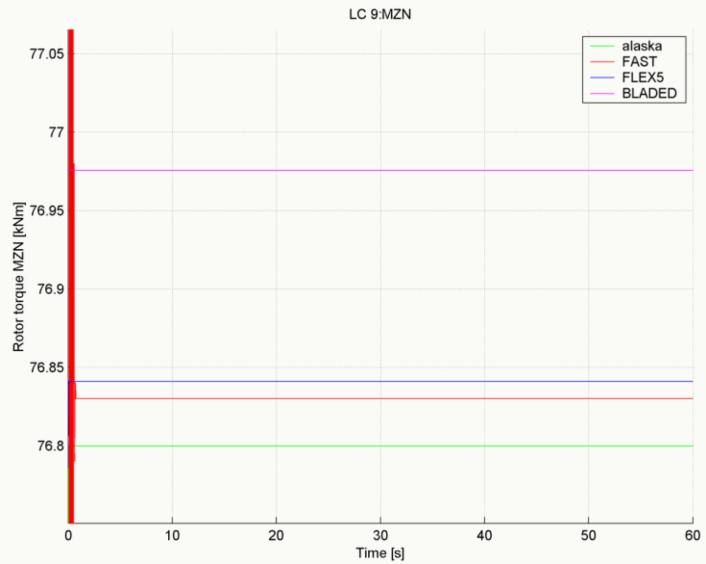
| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Pitch | Yaw | Rotor IC | Generator / Motor | Demanded Rotor Speed | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | Eql/ GDW | None/ Bed/Oye | on/off | on/off | None/Log/Exp | [s] | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | [rpm] | const/var [m/s] | const/var | [on/off] | [s] | [s] |
| 9 | Eql | None | on | off | None | 0.02 | off | off | fixed, 10° | fixed, 0° | 0 | off | - | 8 | 20° | off | 0,02 | 60 |
| 10 | Eql | None | on | off | None | 0.02 | off | on | fixed, 10° | fixed, 0° | 0 | on | 12 | 8 | 20° | off | 0,02 | 200 |
| 11 | Eql | None | on | off | None | 0.02 | off | on | fixed, 10° | fixed, 0° | 0 | on | 12 | 8 | 40° | off | 0,02 | 200 |
| 12 | Eql | None | on | off | None | 0.02 | off | on | fixed, 10° | fixed, 0° | 0 | on | 6 | 8 | 60° | off | 0,02 | 200 |
| 13 | Eql | None | on | off | None | 0.02 | off | on | fixed, 0° | fixed, 0° | 0 | on | 1 | 8 | 80° | off | 0,02 | 200 |
| 14 | Eql | None | on | off | None | 0.02 | off | on | fixed, 10° | fixed, 0° | 0 | off | - | 8 | var1 | off | 0,02 | 320 |

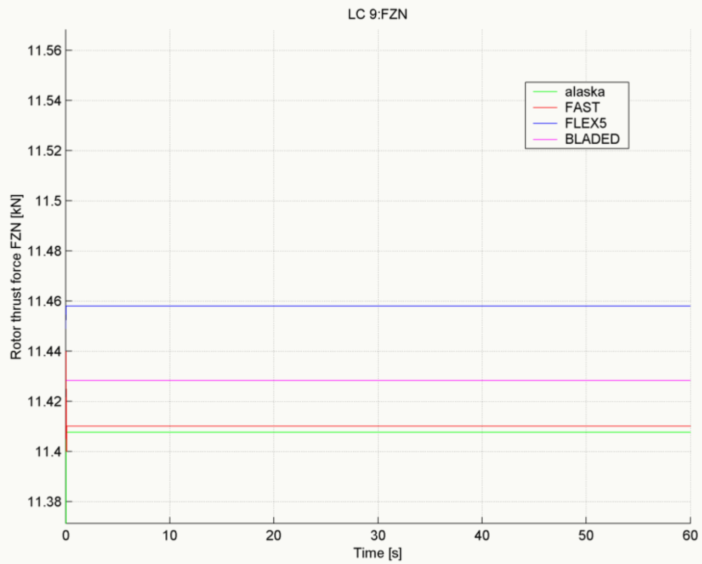
- **wind shear off**
- **tower shadow off**
- **rigid turbine model**
- **stationary rotor speed**

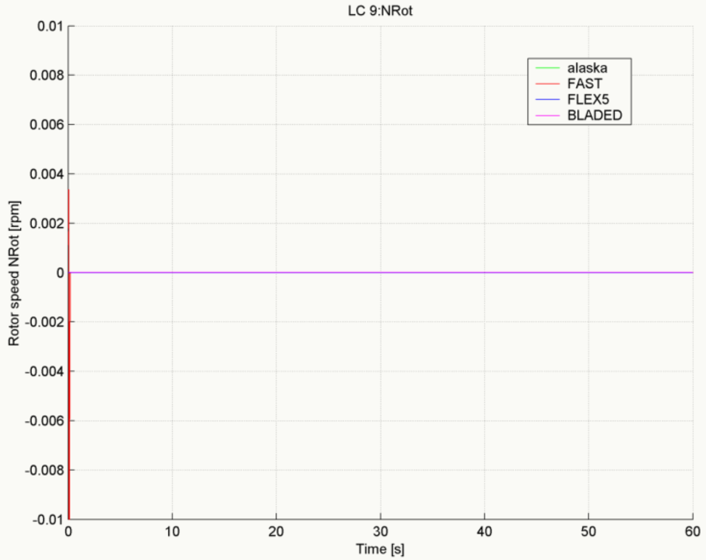
**In LCGroup III, the wind turbine operates at different yaw angles relative to the incoming wind. The load cases 9 to 14 are used to validate the skewed wake correction models.**

# Load Case LC 9, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 10°, Yaw fixed 0°, WindYaw 20°



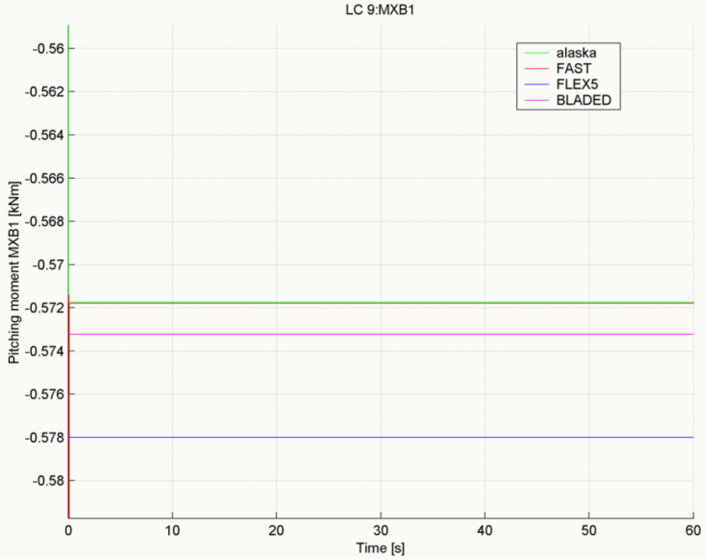


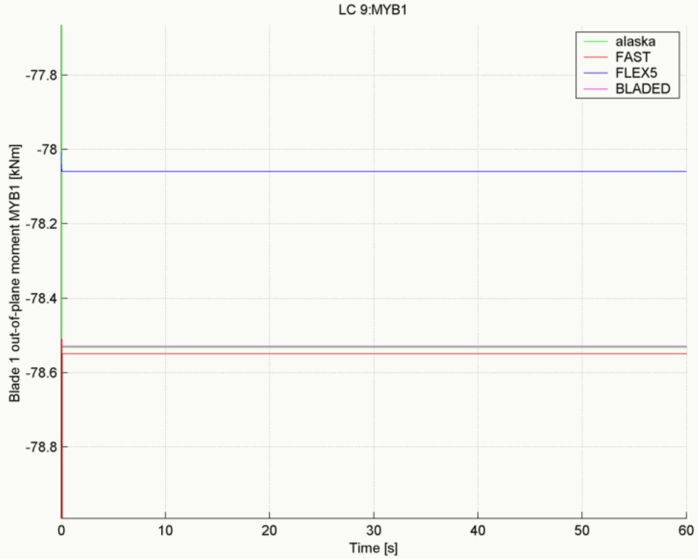



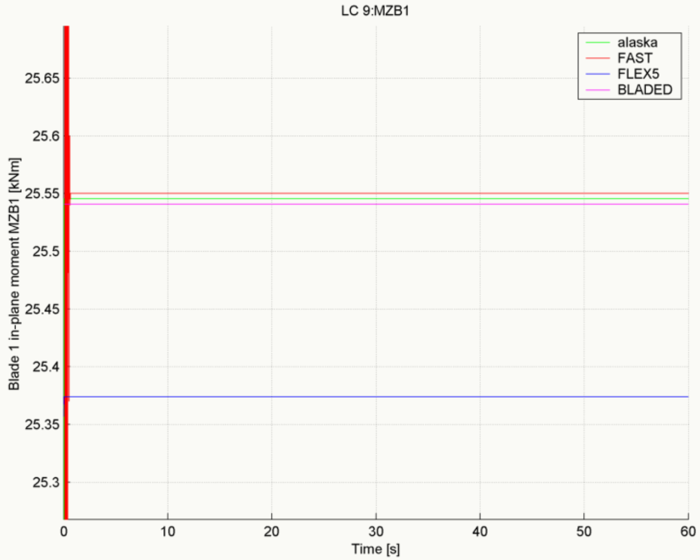



# Load Case LC 9, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 10°, Yaw fixed 0°, WindYaw 20°





# Load Case LC 10, const. Wind = 8 m/s, Rotor stationary 12 rpm, Pitch fixed 10°, Yaw fixed 0°, WindYaw 20°

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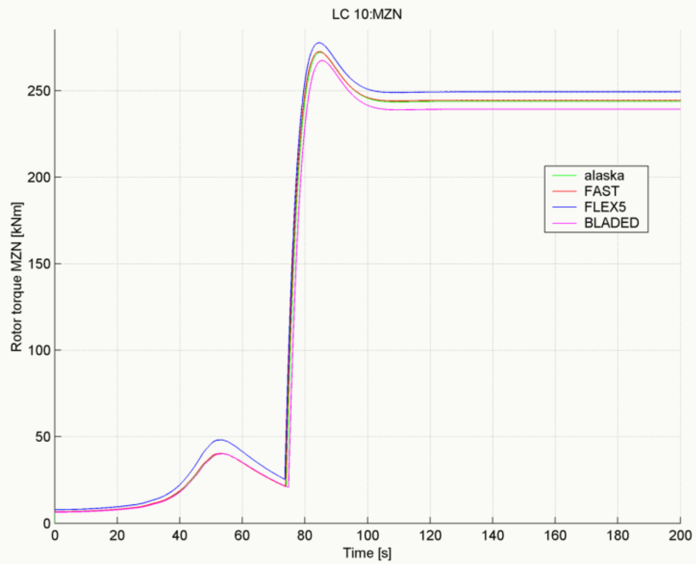
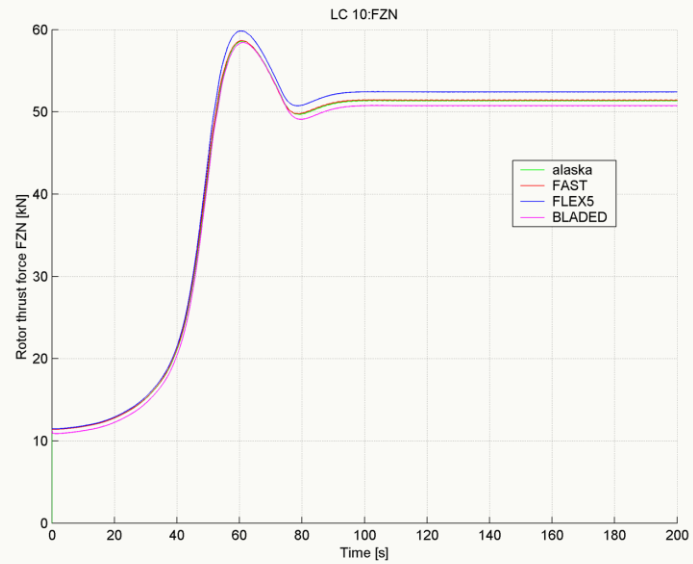
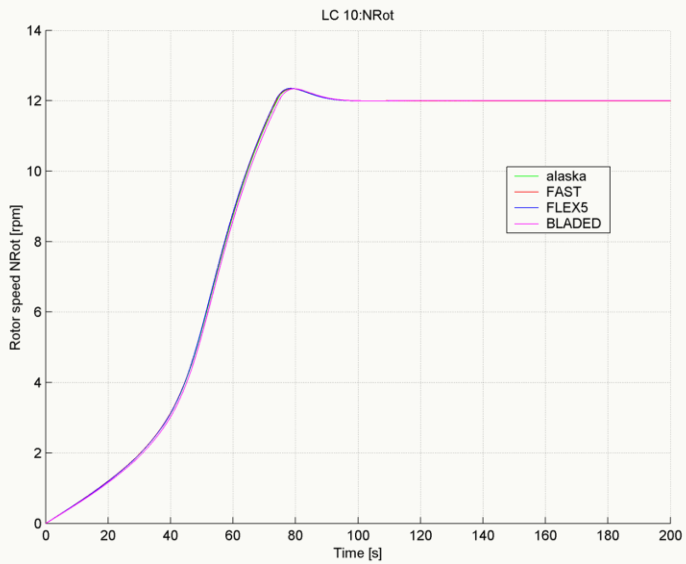
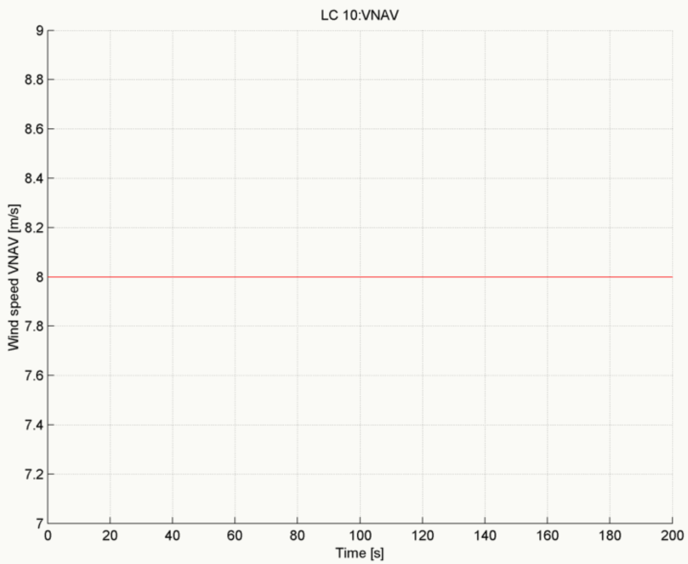


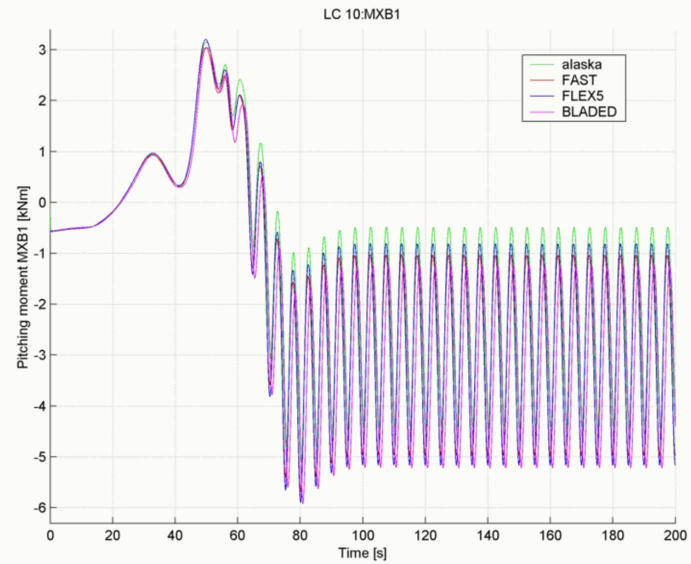



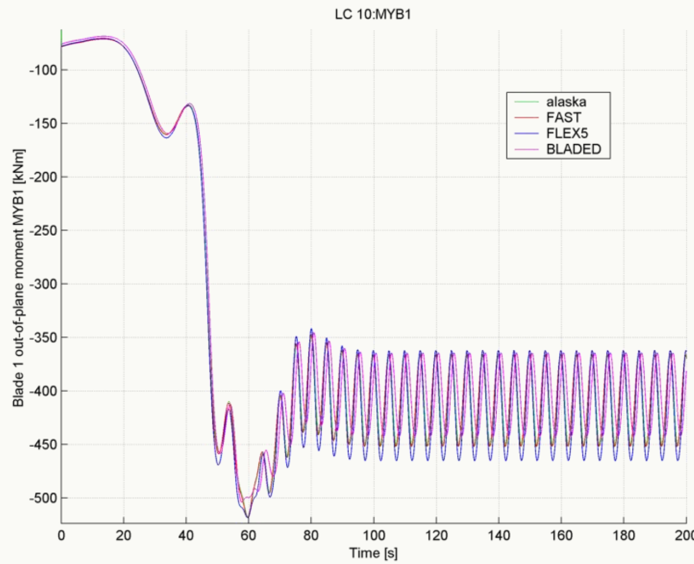



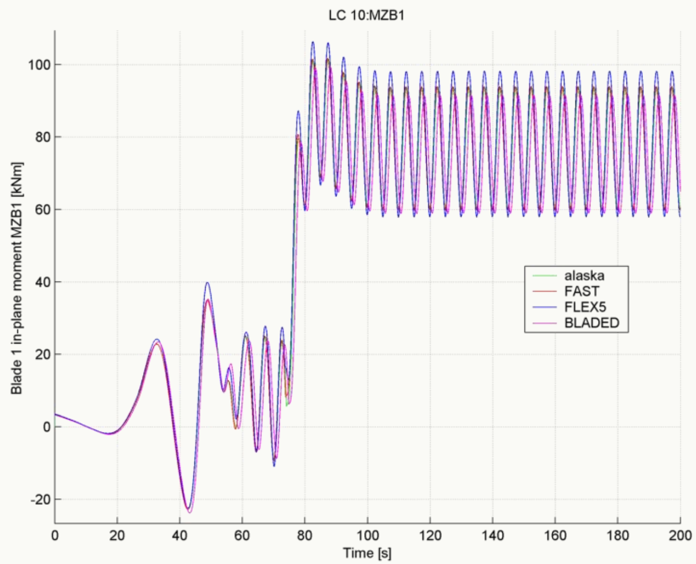



# Load Case LC 10, const. Wind = 8 m/s, Rotor stationary 12 rpm, Pitch fixed 10°, Yaw fixed 0°, WindYaw 20°

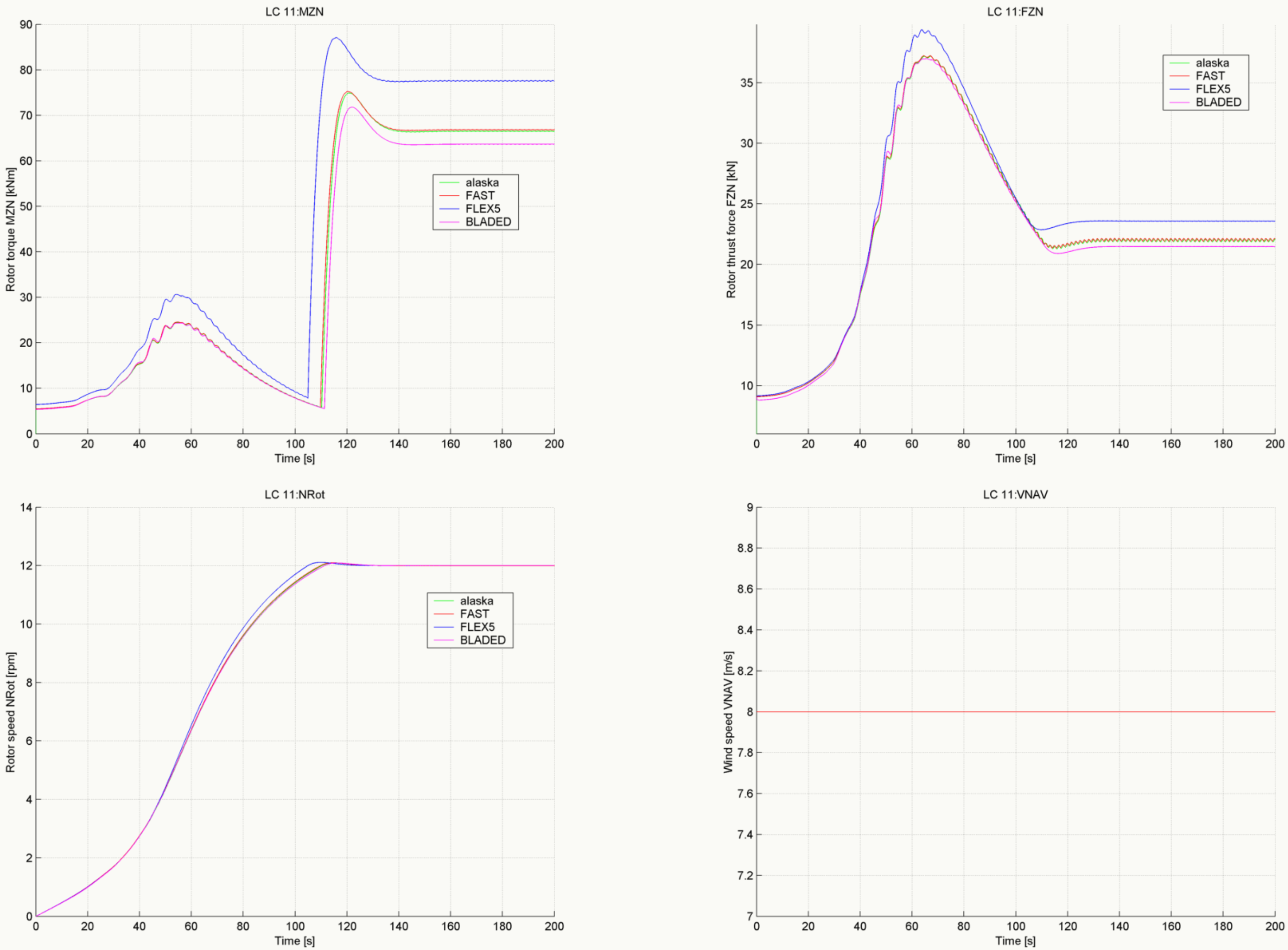




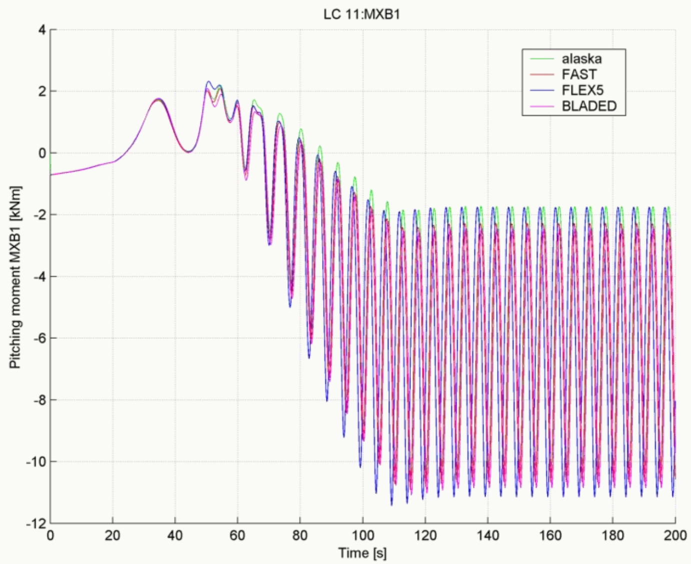



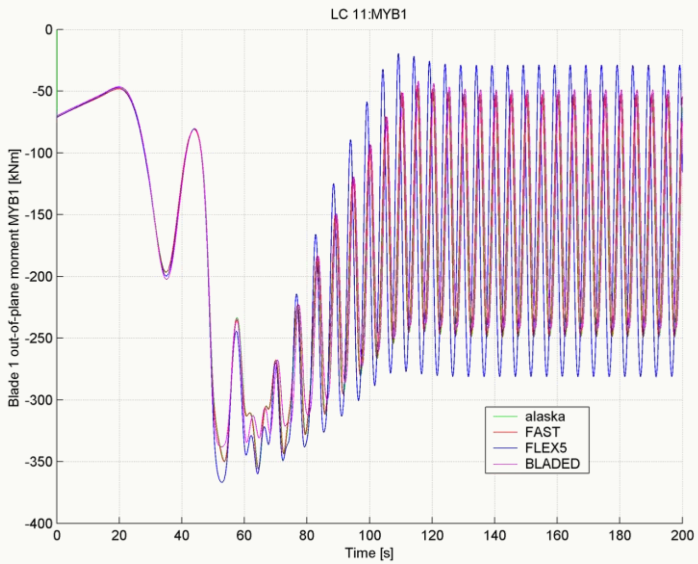
# Load Case LC 11, const. Wind = 8 m/s, Rotor stationary 12 rpm, Pitch fixed 10°, Yaw fixed 0°, WindYaw 40°

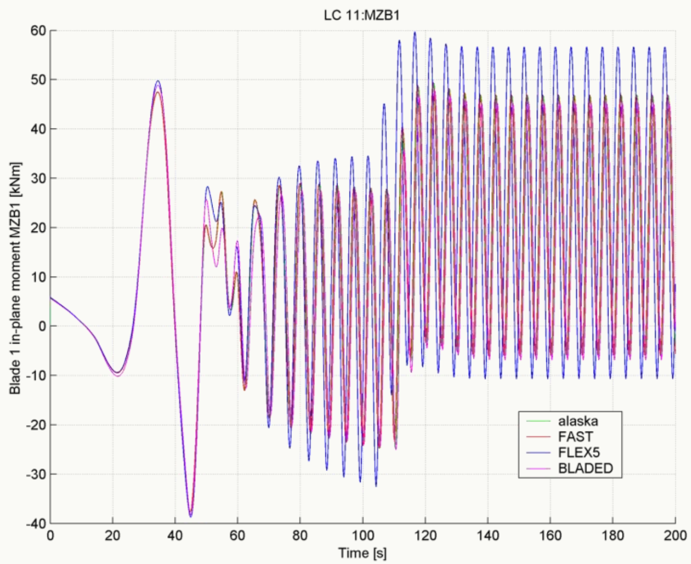


# Load Case LC 11, const. Wind = 8 m/s, Rotor stationary 12 rpm, Pitch fixed 10°, Yaw fixed 0°, WindYaw 40°





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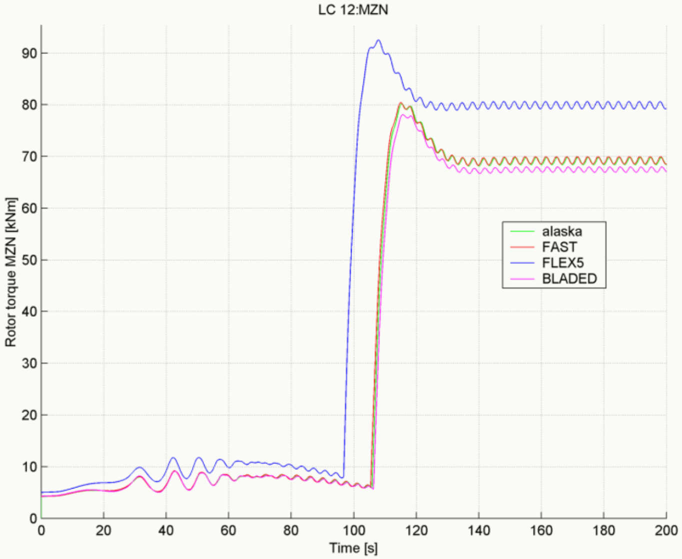


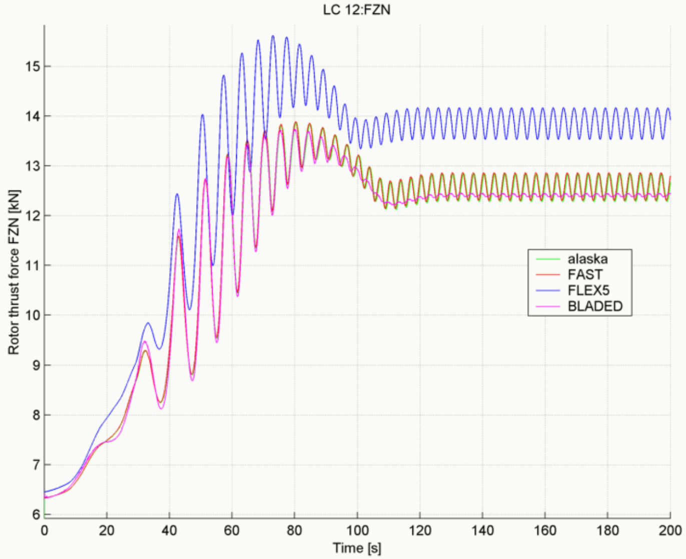


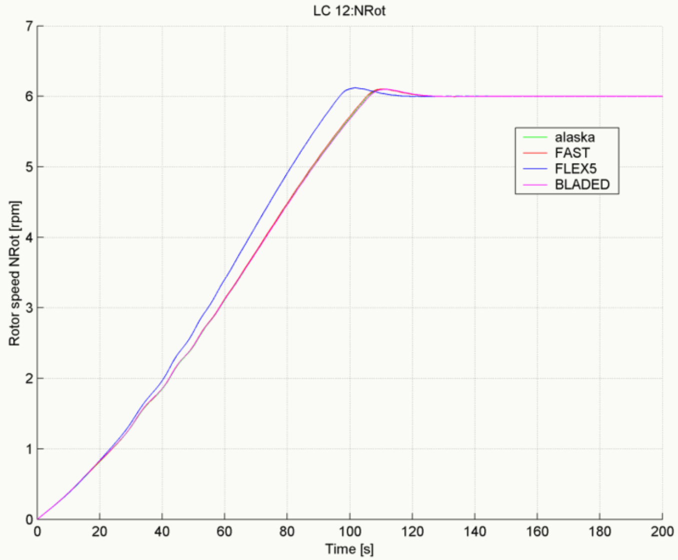


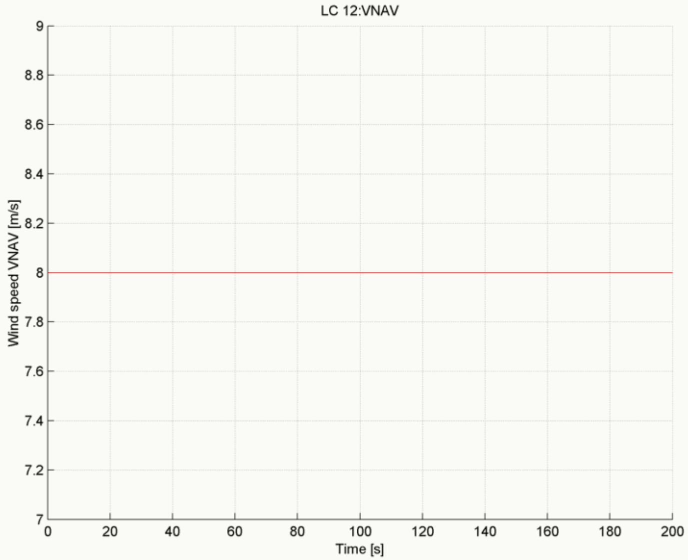

# Load Case LC 12, const. Wind = 8 m/s, Rotor stationary 6 rpm, Pitch fixed 10°, Yaw fixed 0°, WindYaw 60°

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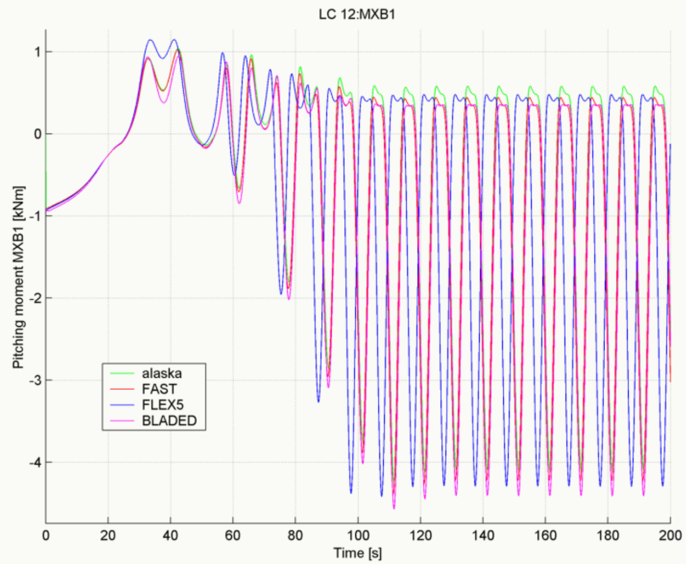


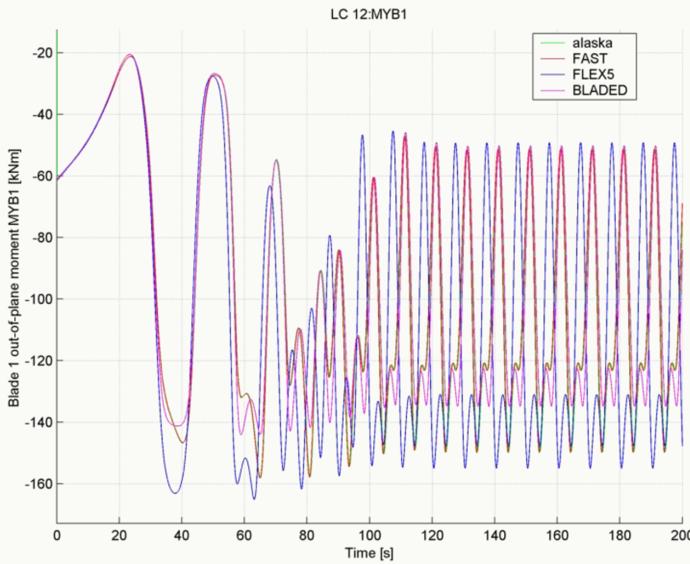


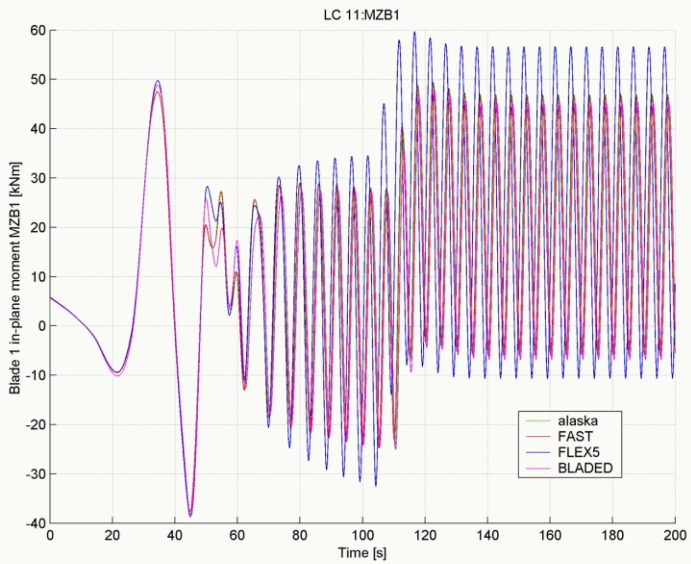

# Load Case LC 13, const. Wind = 8 m/s, Rotor stationary 1 rpm, Pitch fixed 0°, Yaw fixed 0°, WindYaw 80°

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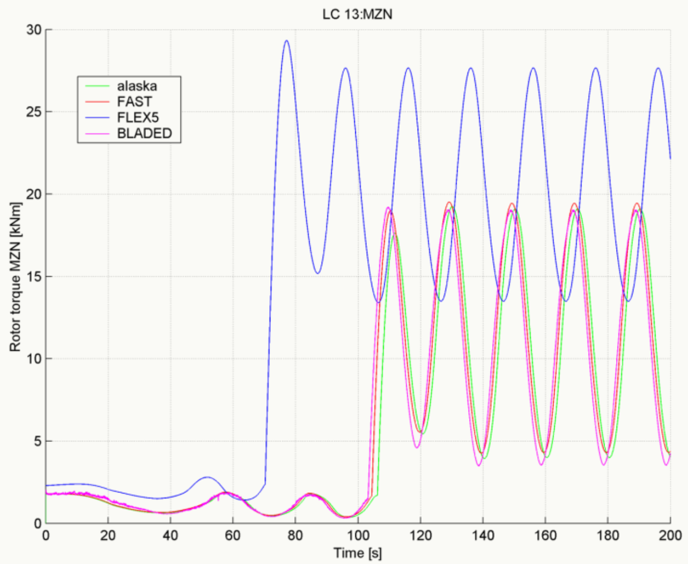
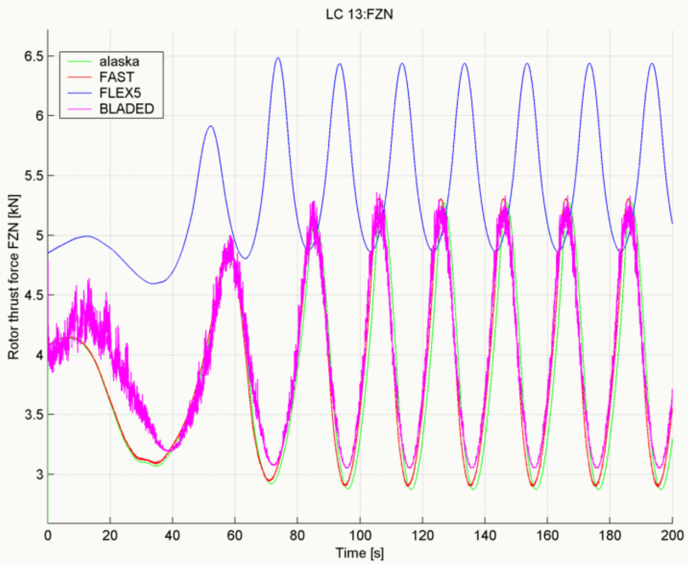
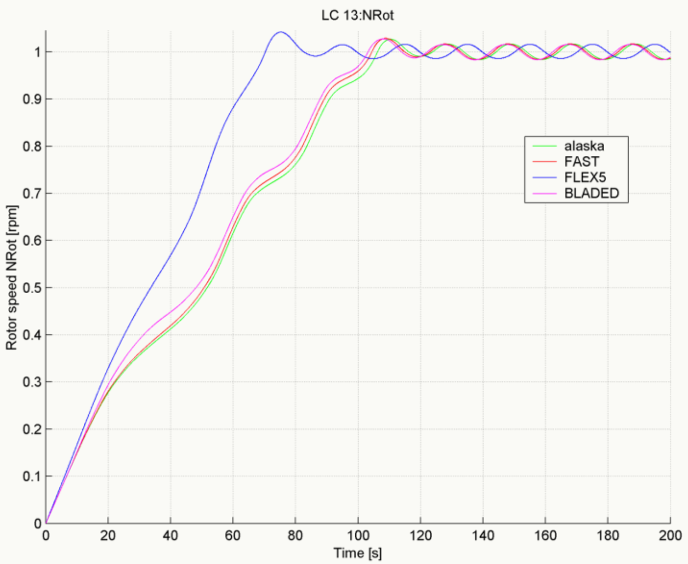
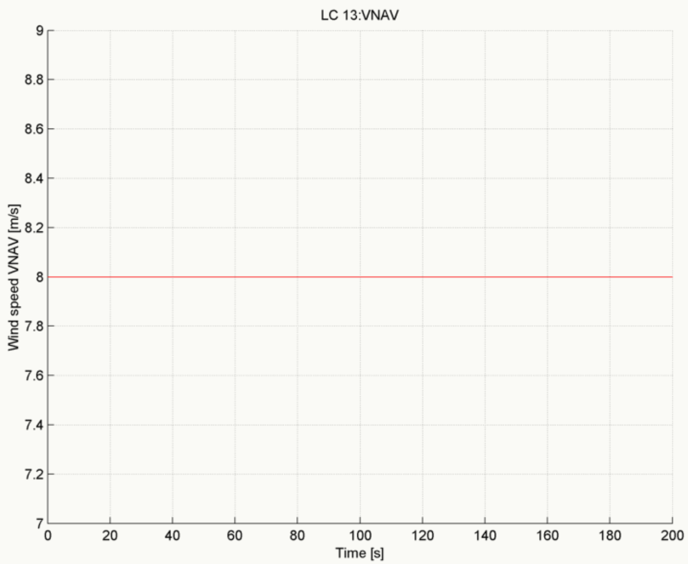
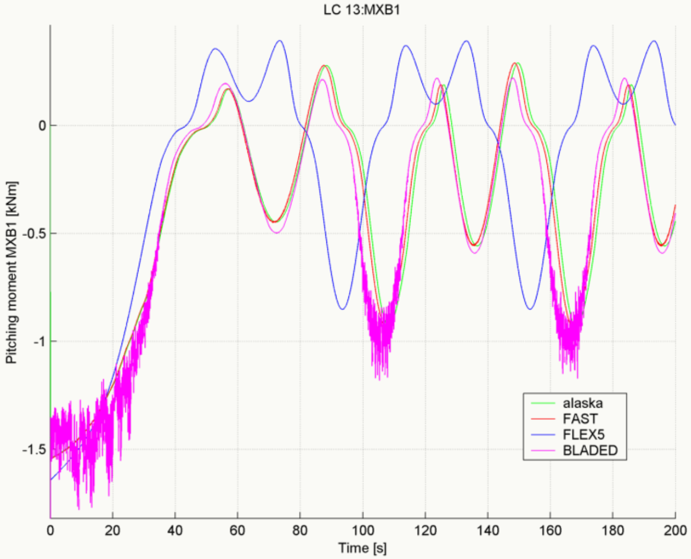


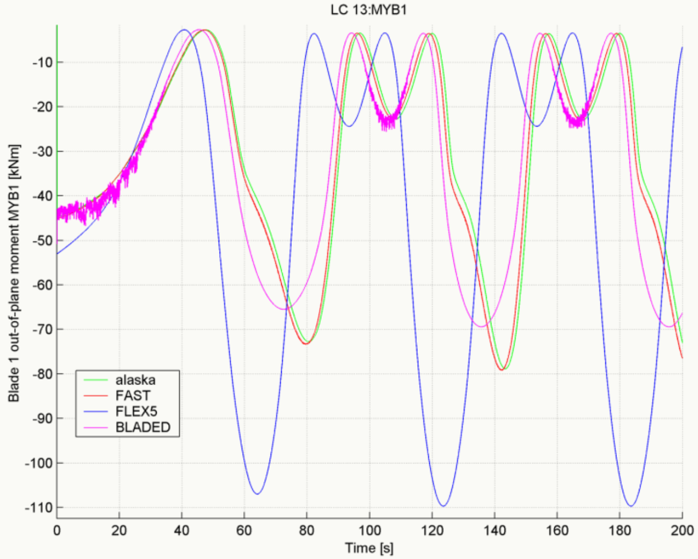



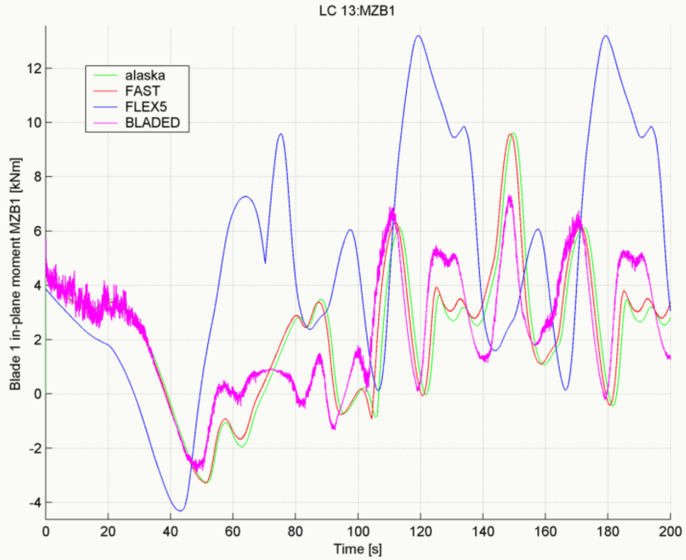



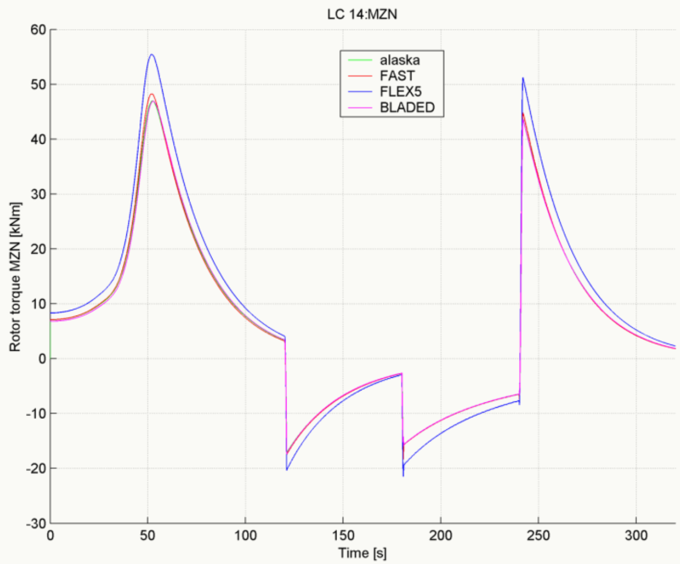



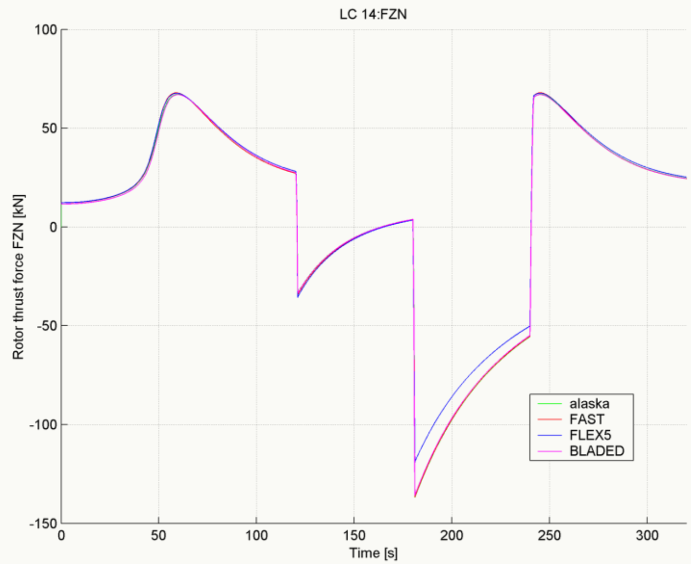
# Load Case LC 13, const. Wind = 8 m/s, Rotor stationary 1 rpm, Pitch fixed 0°, Yaw fixed 0°, WindYaw 80°

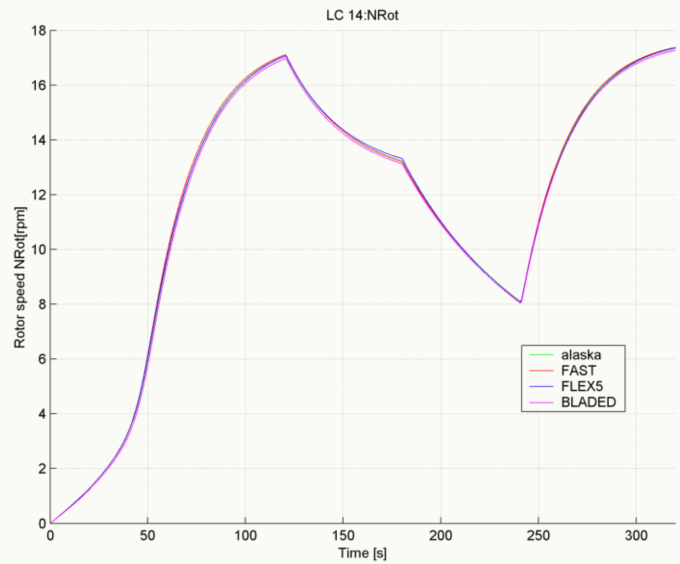


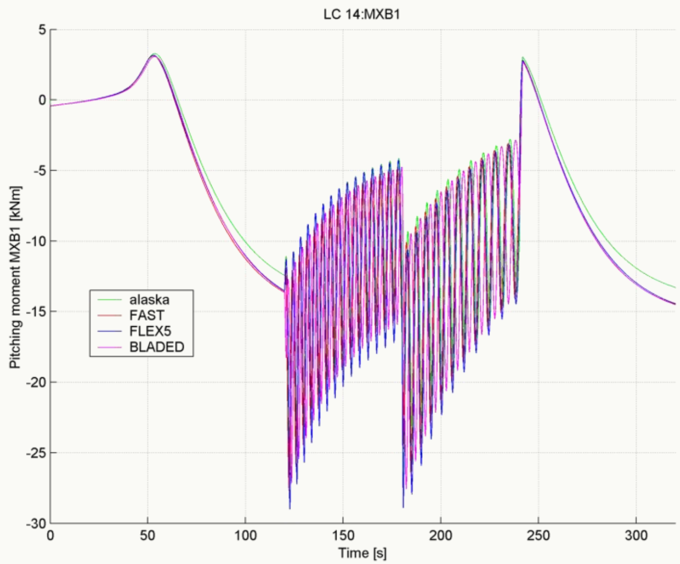



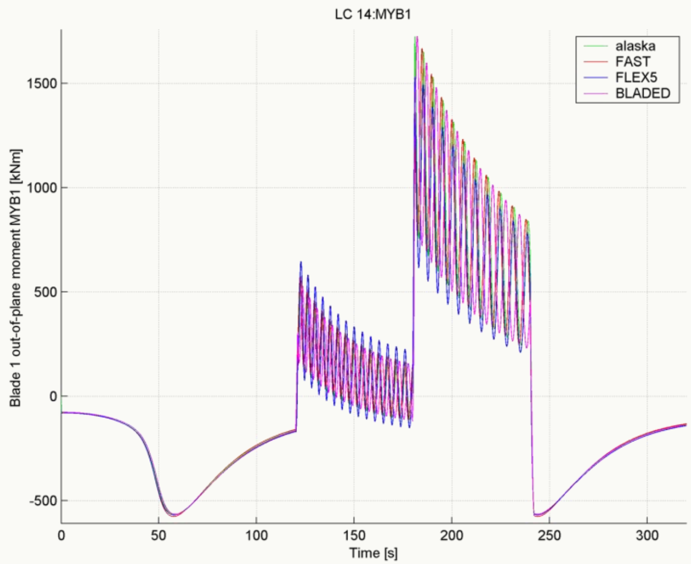



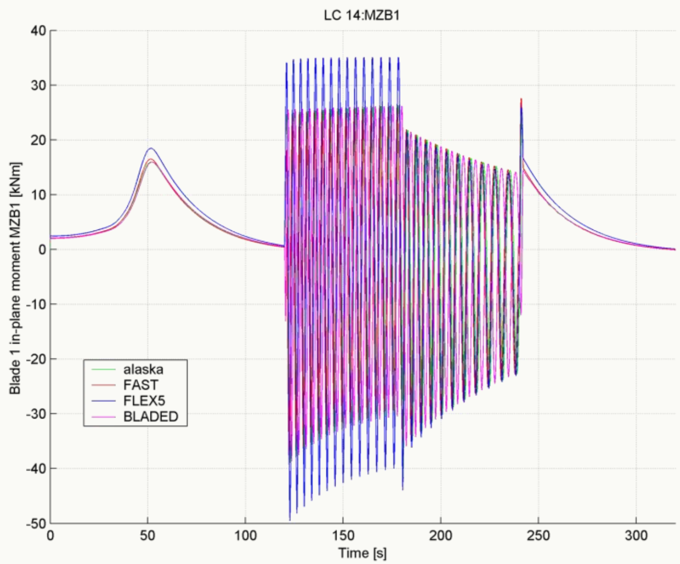

LC 14:MZN
Rotor torque MZN [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC 14:FZN
Rotor thrust force FZN [kN]
Time [s]
alaska
FAST
FLEX5
BLADED


LC 14:NRot
Rotor speed NRot[rpm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC 14:MXB1
Pitching moment MXB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC 14:MYB1
Blade 1 out-of-plane moment MYB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED

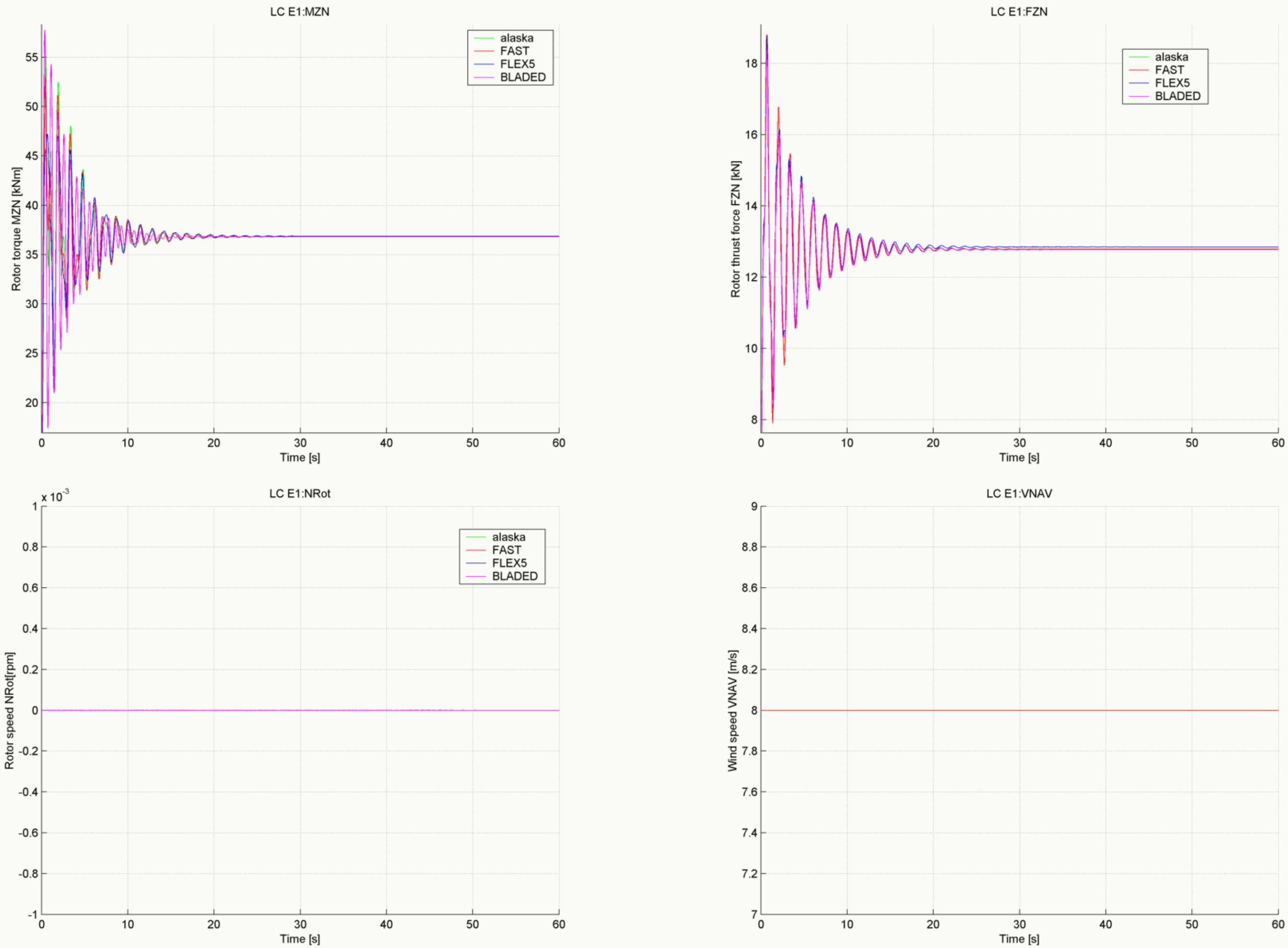

LC 14:MZB1
Blade 1 in-plane moment MZB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED

## LCGroup I_Elastic

| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Blade DOF 2 Flap, 1 Edge | Tower DOF 2 side-to-side 2 fore-aft | Pitch | Yaw | Rotor IC | Generator / Motor | Demanded Rotor Speed | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | Eql/ GDW | None/ Bed/Oye | on/ off | on/ off | None/ Log/Exp | [s] | on/off | on/off | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | [rpm] | const/ var [m/s] | const/ var | [on/off] | [s] | [s] |
| E1 | Eql | None | on | off | None | 0.02 | off | off | on | off | fixed, 0° | fixed, 0° | 0 | off | - | 8 | 0° | off | 0,02 | 300 |
| E3 | Eql | None | on | off | None | 0.02 | off | off | on | off | fixed, 0° | fixed, 0° | 0 | off | - | var1 | 0° | off | 0,02 | 300 |
| E4_1 | Eql | None | on | off | None | 0.02 | off | on | on | off | fixed, 0° | fixed, 0° | 0 | on | 15 | var2 | 0° | off | 0,02 | 300 |
| E5_1 | Eql | None | on | off | None | 0.02 | off | on | on | off | fixed, 0° | fixed, 0° | 0 | on | 15 | 8 | 0° | off | 0,02 | 300 |
| E7_1 | Eql | None | on | off | None | 0.02 | off | on | on | off | fixed, 0° | fixed, 0° | 8 | on | 15 | var3 | 0° | off | 0,02 | 500 |
| E8_1 | Eql | None | on | off | None | 0.02 | off | on | on | off | fixed, 10° | fixed, 0° | 8 | on | 15 | var4 | 0° | off | 0,02 | 350 |
| E15 | Eql | None | on | off | None | 0.02 | off | off | off | on | fixed, 0° | fixed, 0° | 0 | off | - | var5 | 0° | off | 0,02 | 100 |

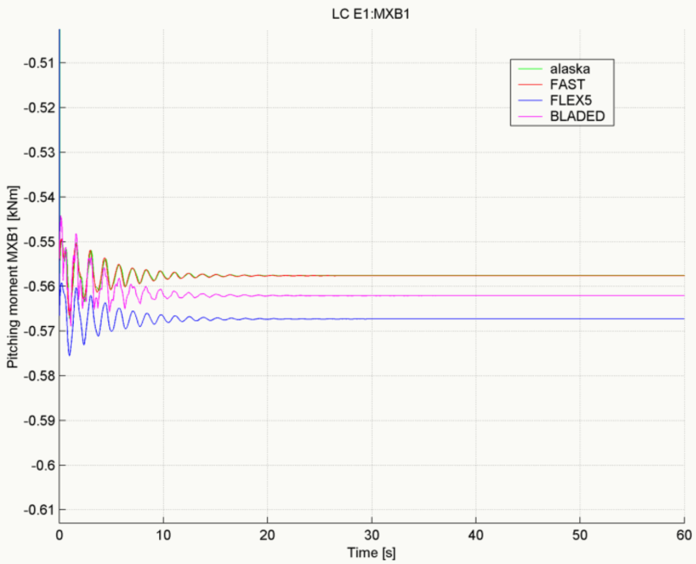
- **wind shear off**
- **tower shadow off**
- **flexible blade model**
- **flexible tower model**

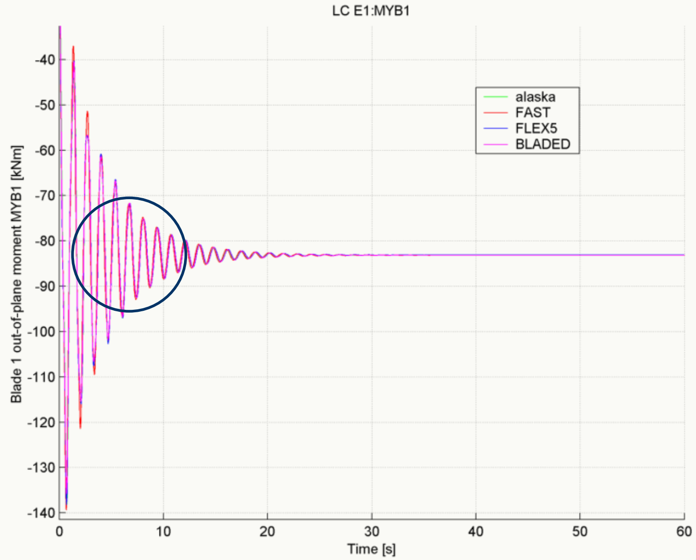
**In LCGroup I_Elastic, the load cases of LCGroup II has been repeated with flexible blades or a flexible tower. The effect of flexible components on the turbine model behavior has been investigated. As results, blade and tower forces, moments and deflections are recorded.**

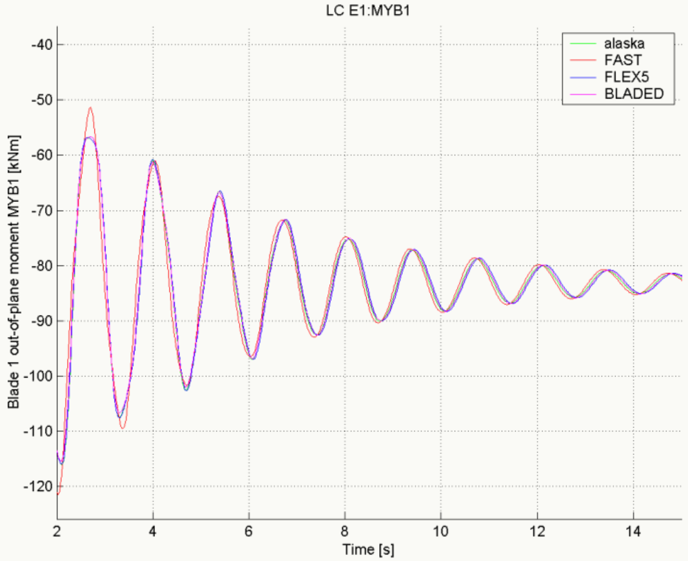


LC E1:MZN
alaska
FAST
FLEX5
BLADED
Rotor torque MZN [kNm]
Time [s]
LC E1:FZN
Rotor thrust force FZN [kN]
LC E1:NRot
x 10^-3
Rotor speed NRot[rpm]
LC E1:VNAV
Wind speed VNAV [m/s]

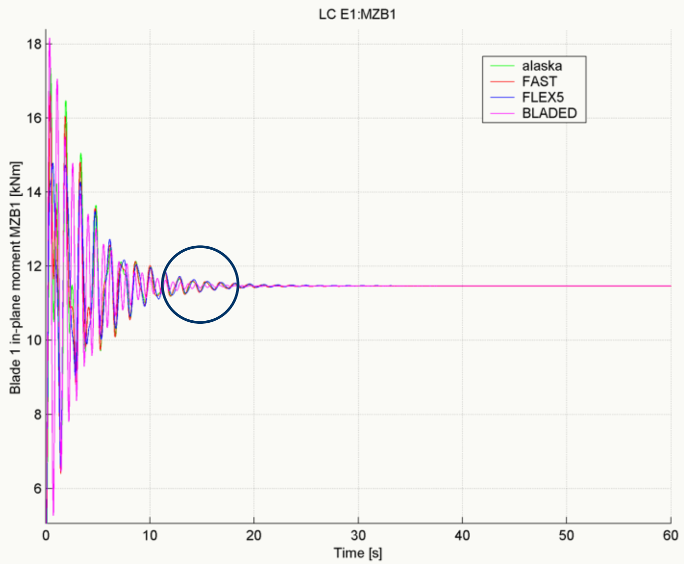
# Load Case LC E1, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

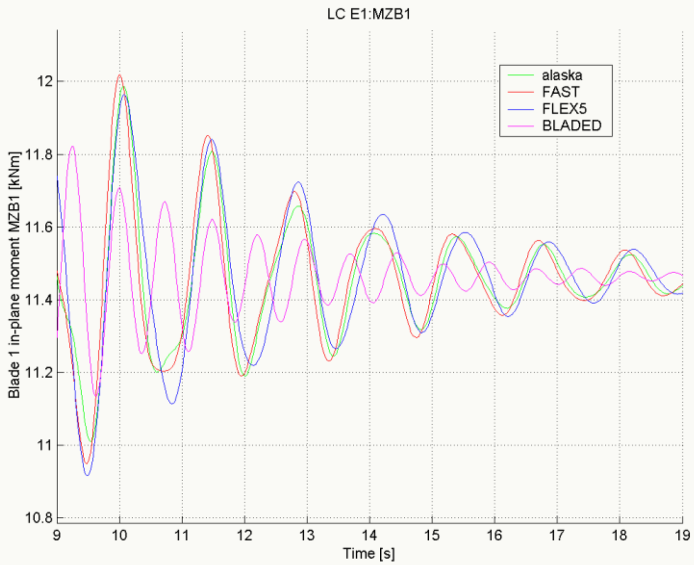


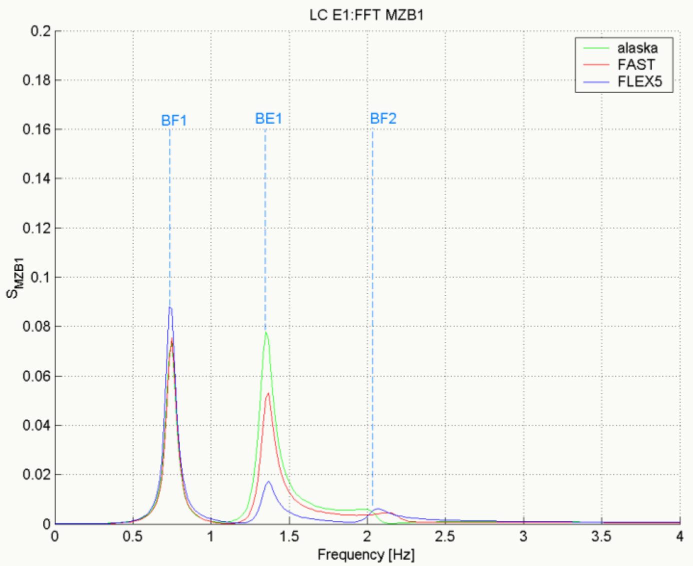



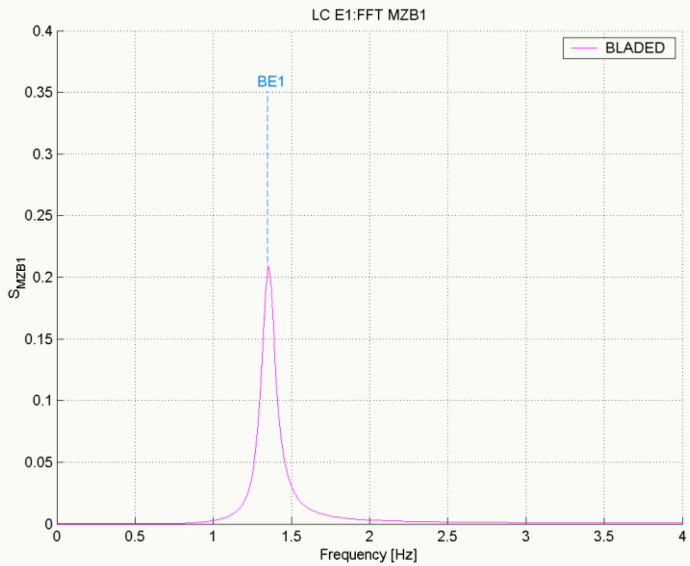



# Load Case LC E1, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible



# Load Case LC E1, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

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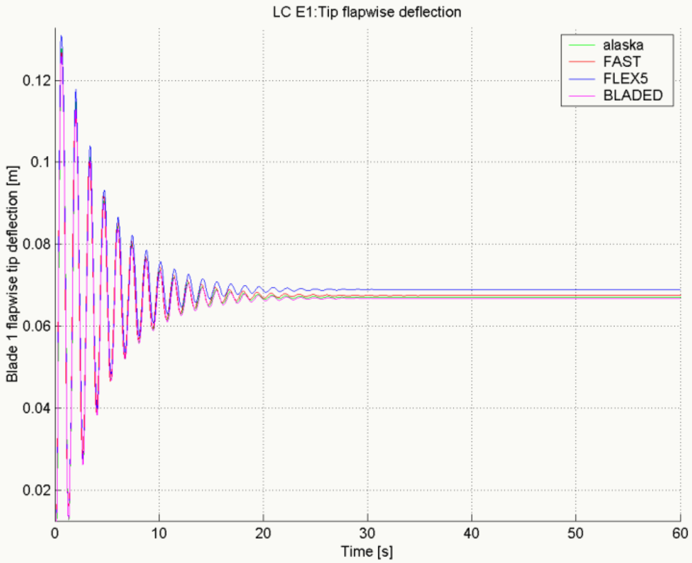
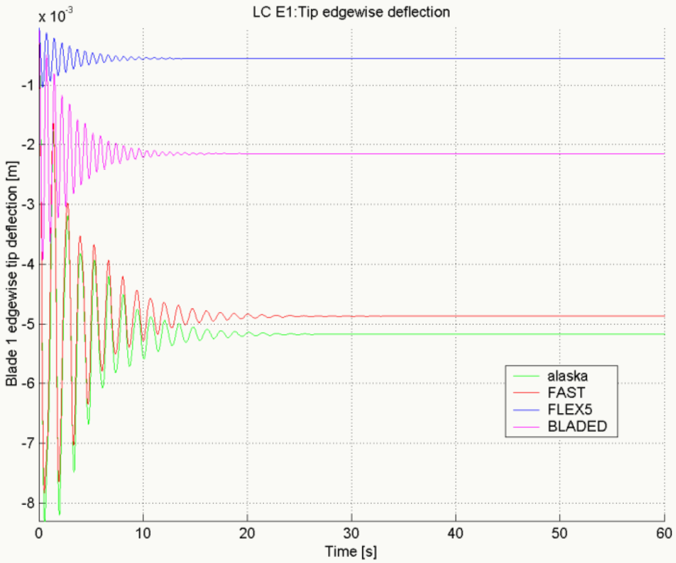


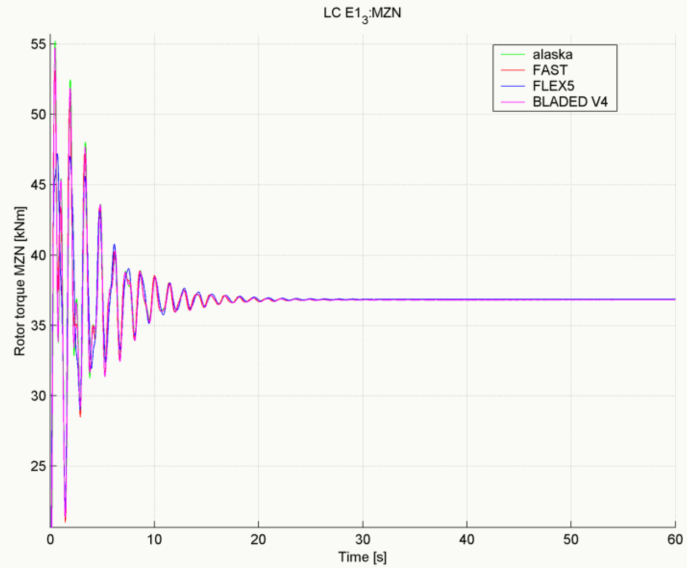



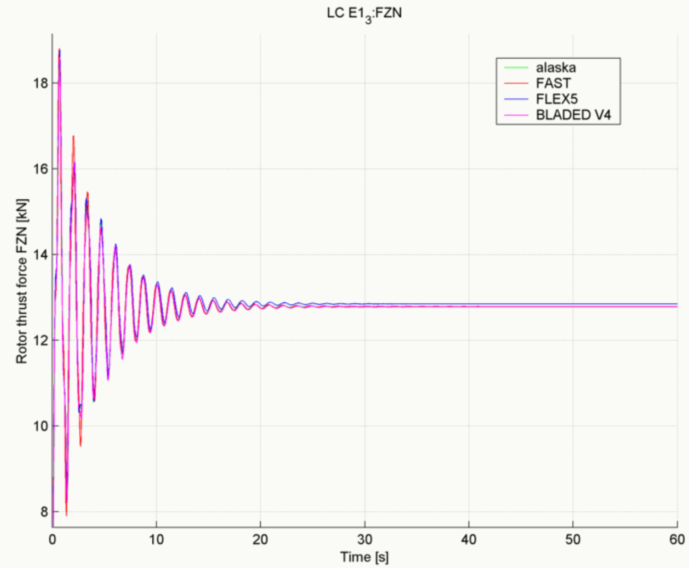
# Load Case LC E1_3, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

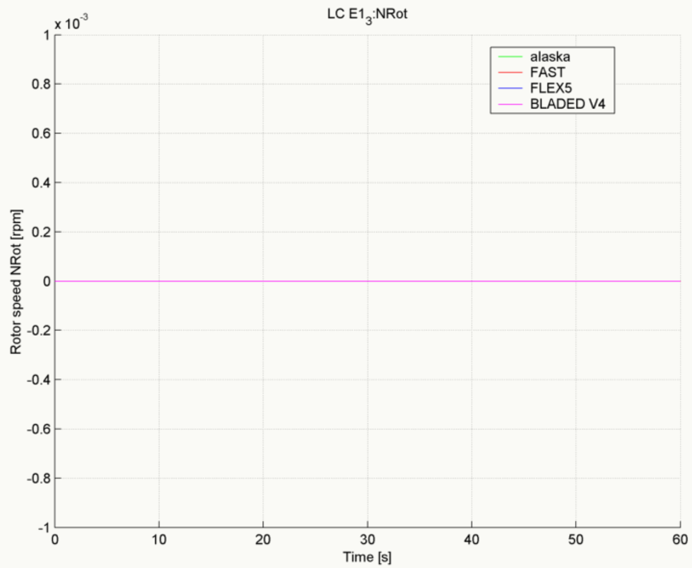


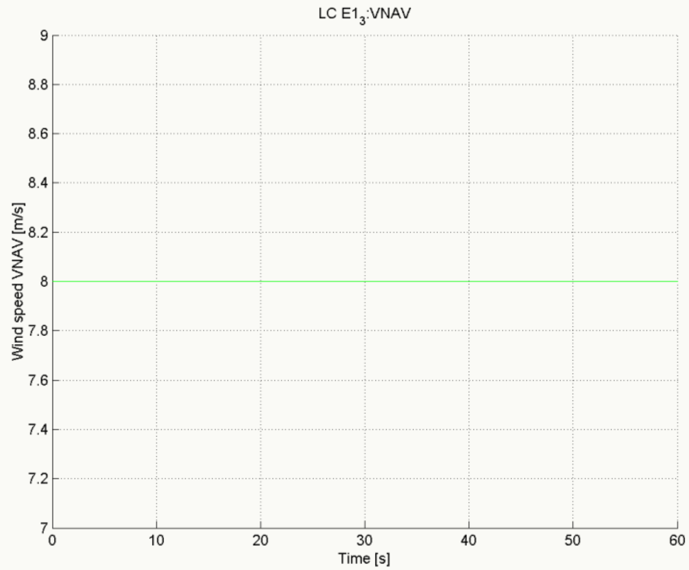
**The load case LC E1_3 is equivalent to load case LC E1 except that the new Multibody Dynamics BLADED V4 has been used instead of BLADED V3.82. According to GL Garrad Hassan, in BLADED V4 they switched from rotor modes to fully coupled individual blade modes which are valid for any pitch angle. This blade model seems to be similar to the flexible body approach used in alaska/Wind for the blade model. Running load case LC E1 with BLADED V4 gave us the opportunity to investigate some of the recognized differences in the results of LC E1 and we also were able to validate the flexible body blade model of alaska/Wind in comparison with BLADED V4.**

# Load Case LC E1_3, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

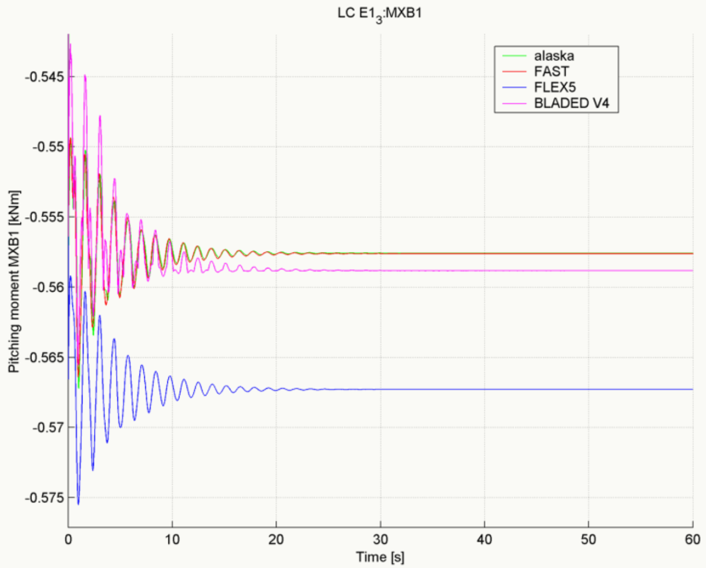


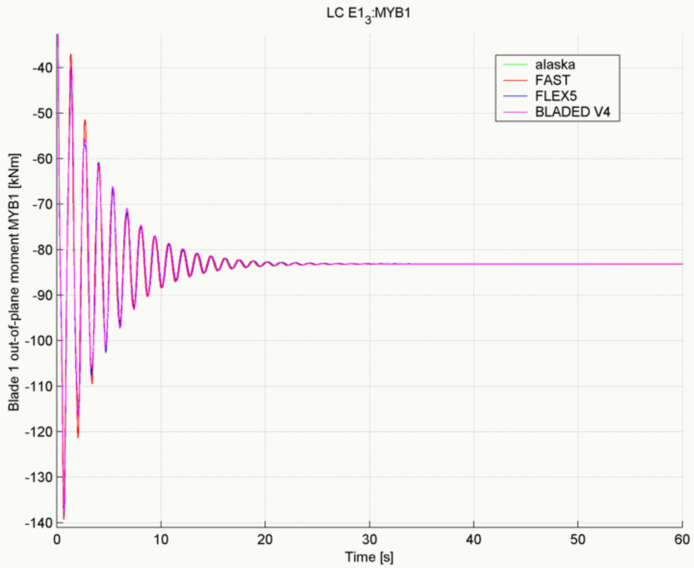



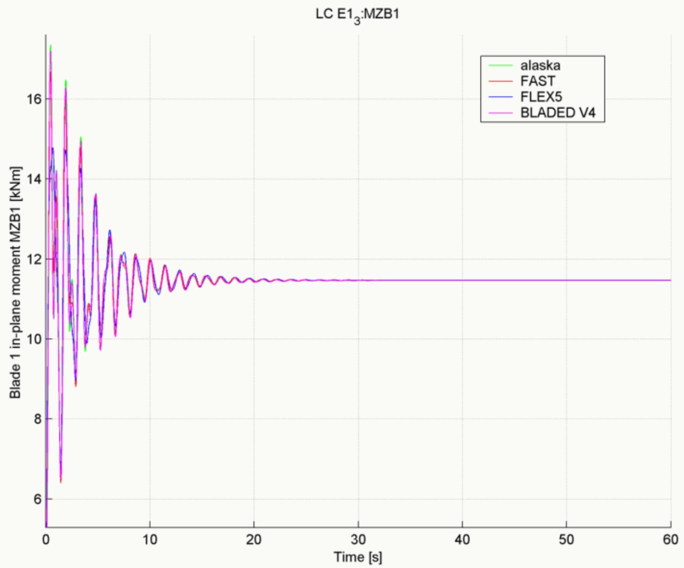



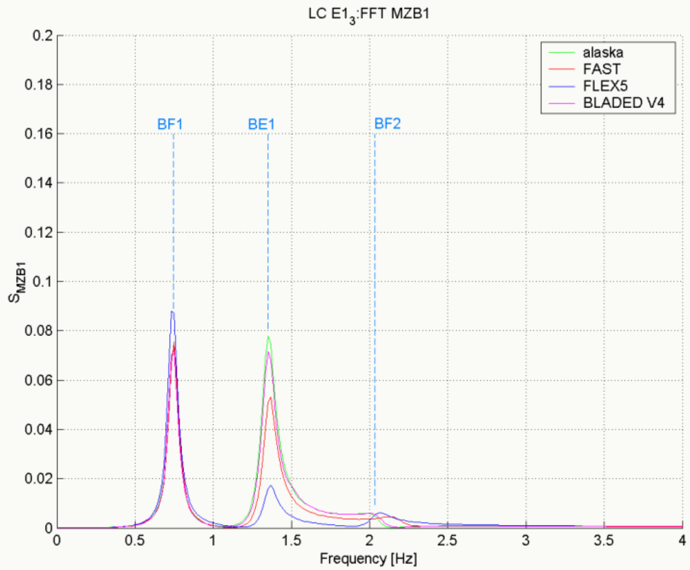



# Load Case LC E1_3, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4



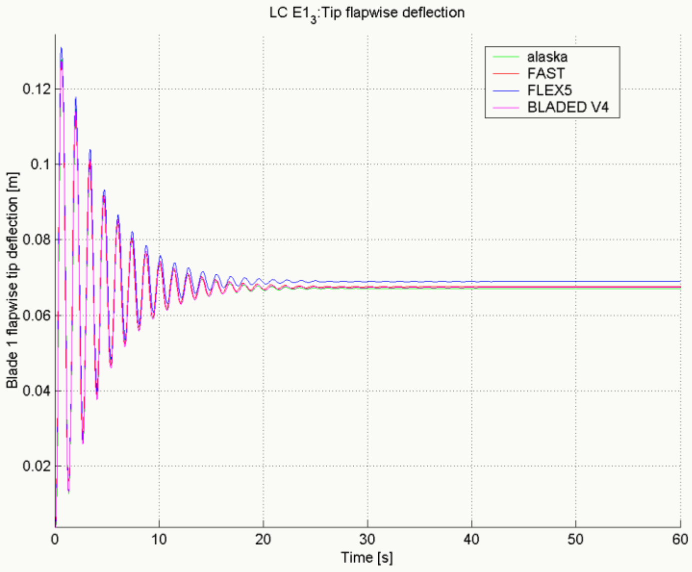



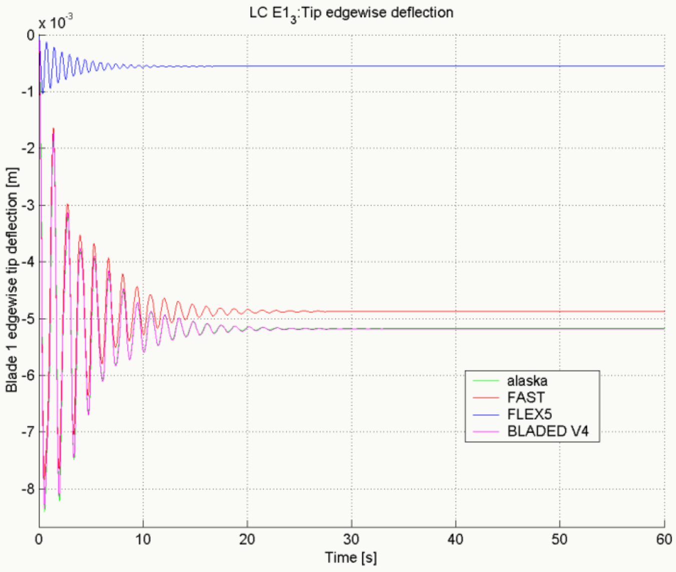



# Load Case LC E1_3, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4





# Load Case LC E1_3, const. Wind = 8 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

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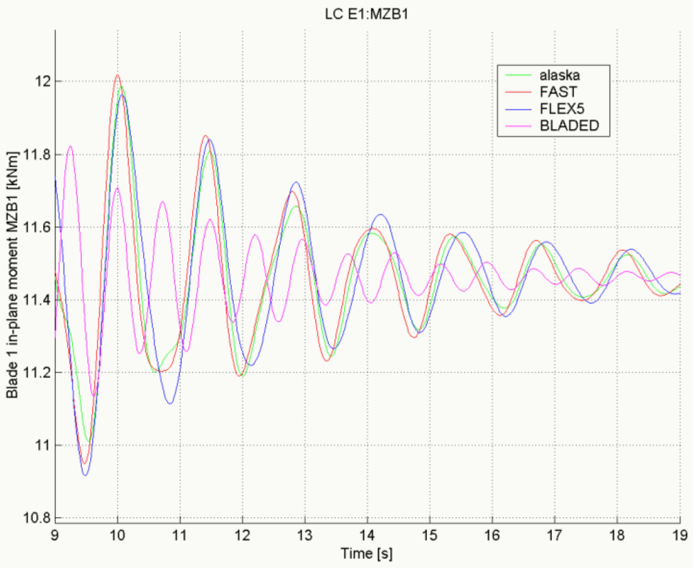
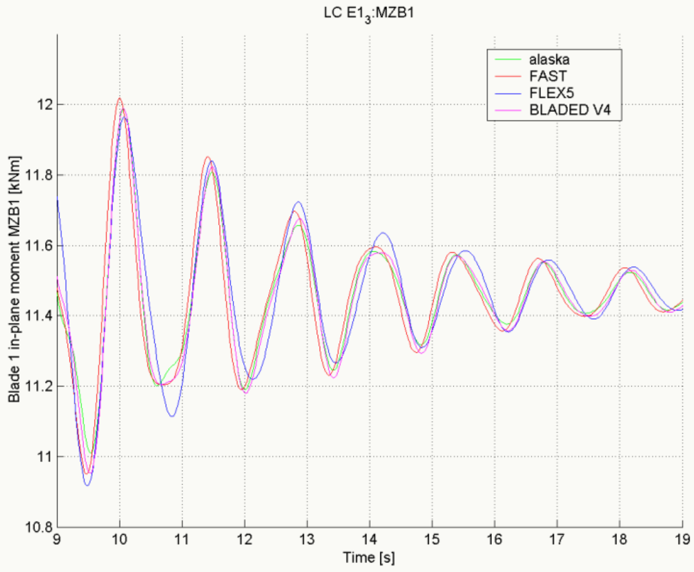
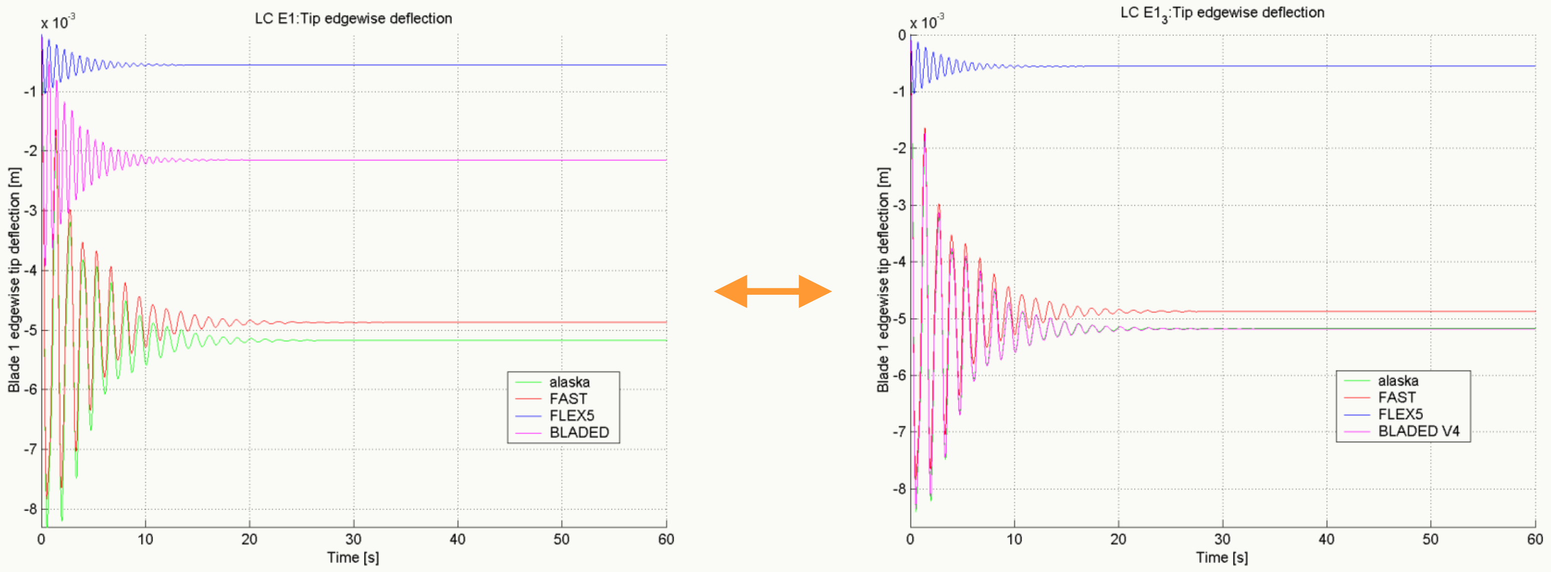
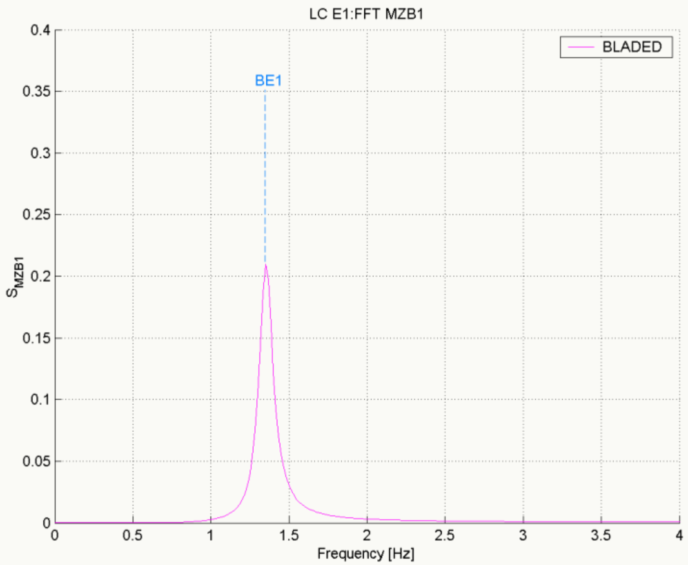


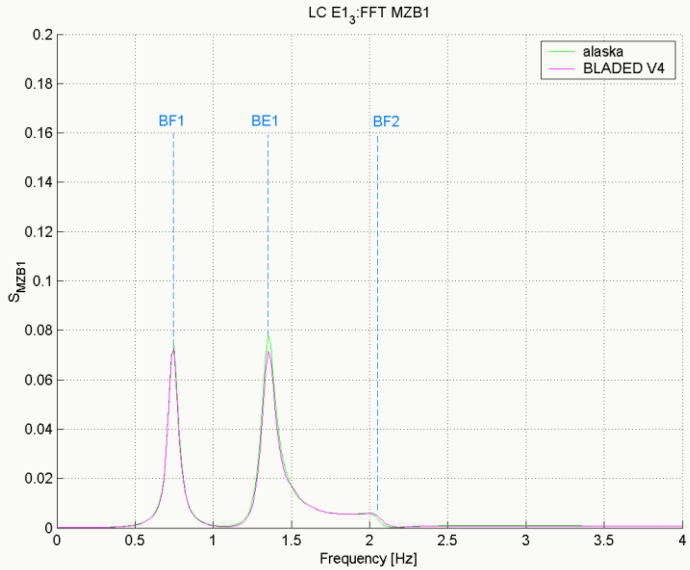




**Blade 1 in-plane moment for BLADED V3.82 and BLADED V4**




**Blade 1 edgewise tip deflection for BLADED V3.82 and BLADED V4**

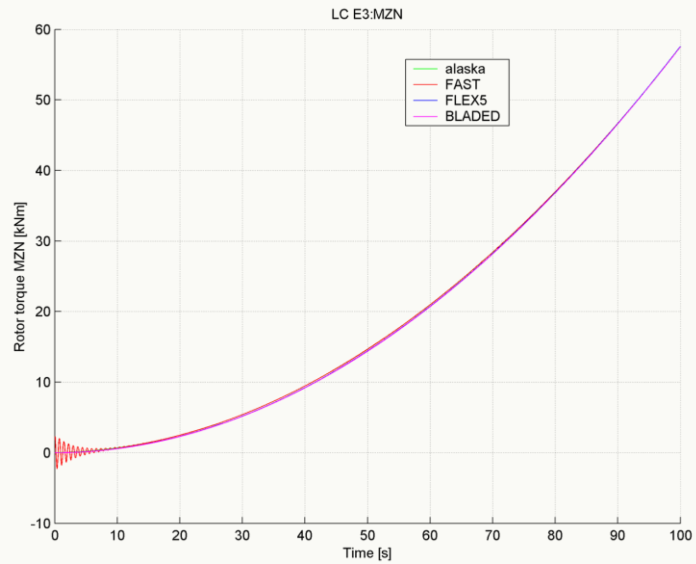


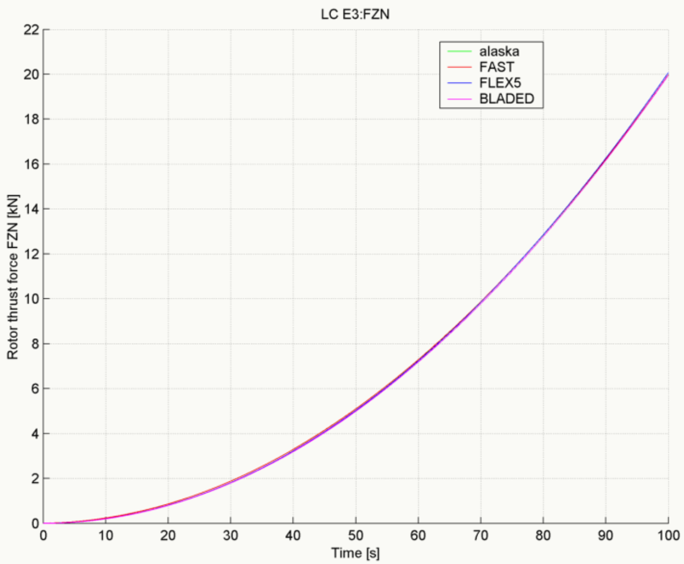



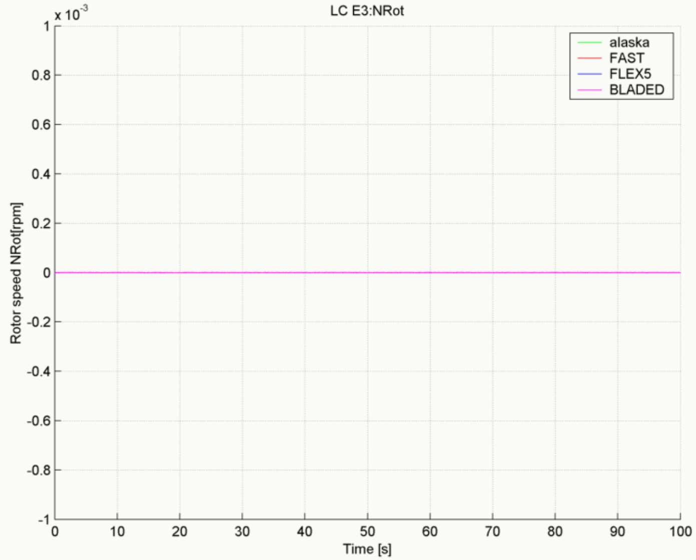

**frequency spectrum of blade 1 in-plane moment for BLADED V3.82 and BLADED V4**

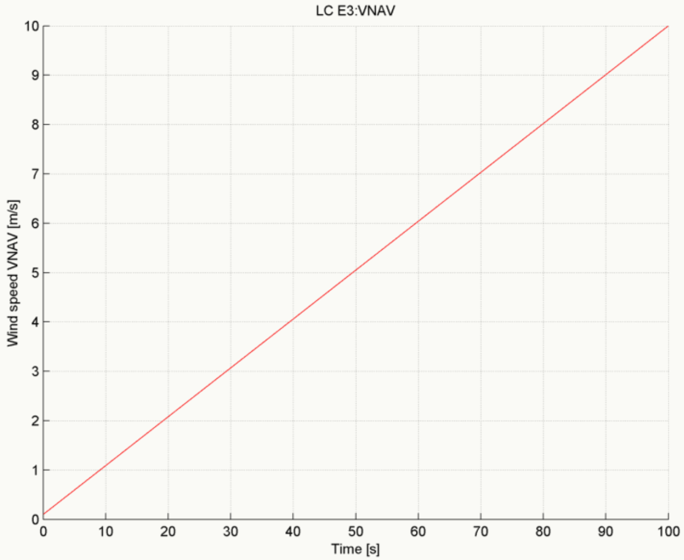
# Load Case LC E3, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible



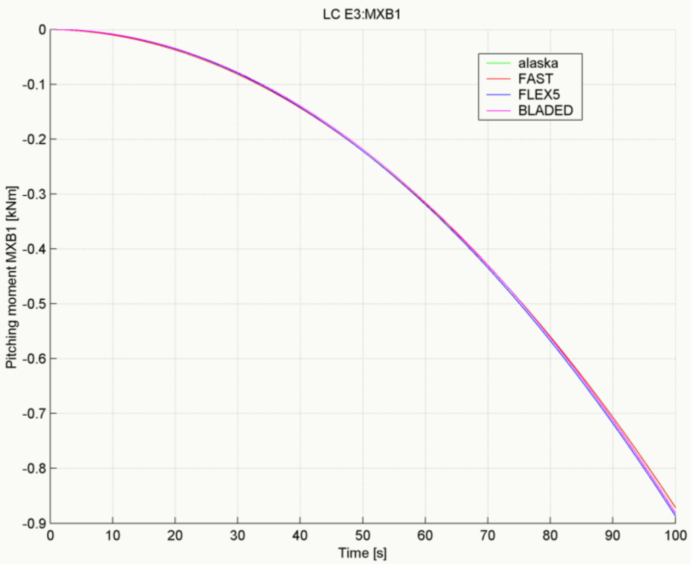


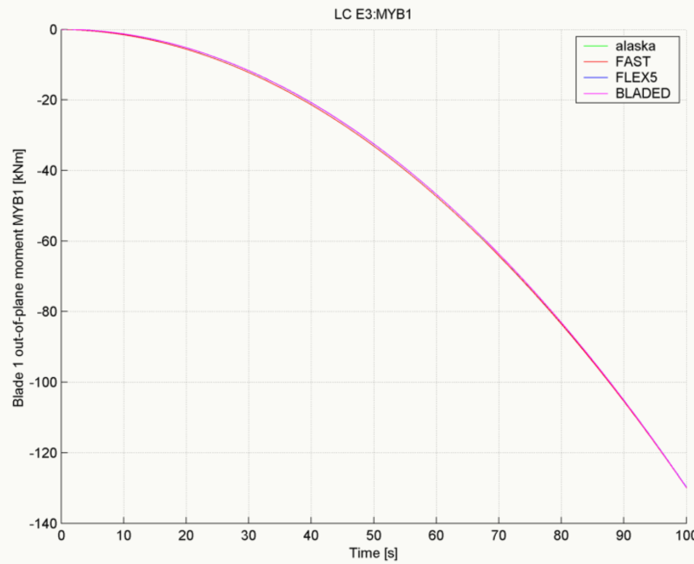



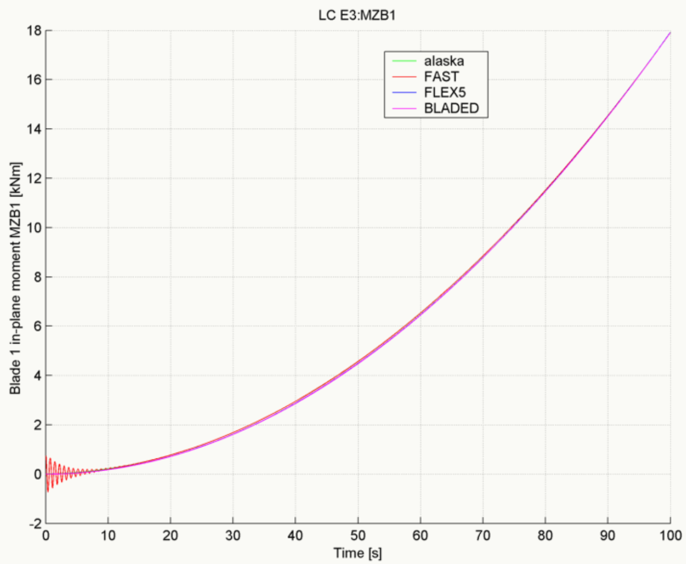



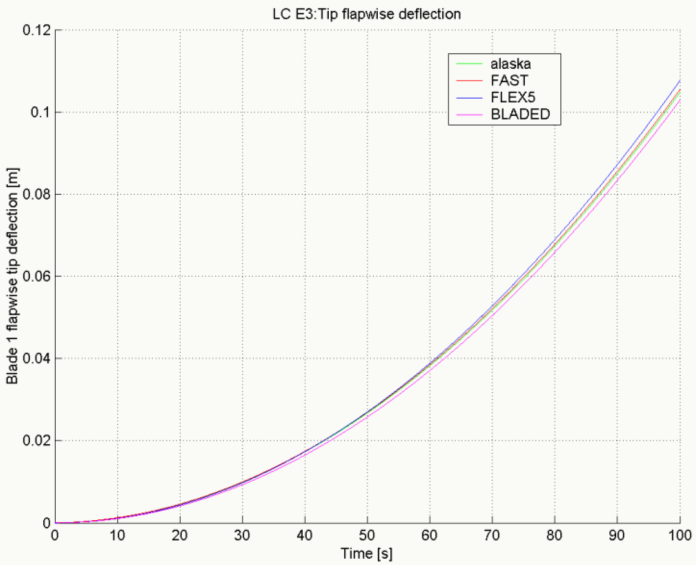
# Load Case LC E3, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

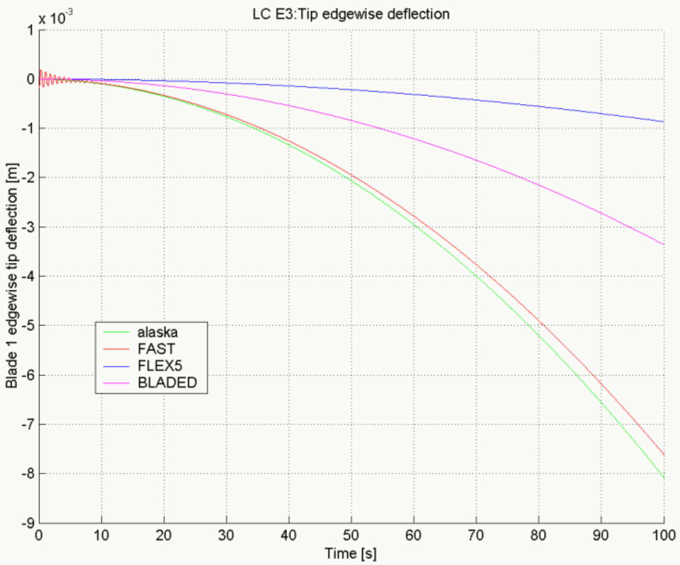


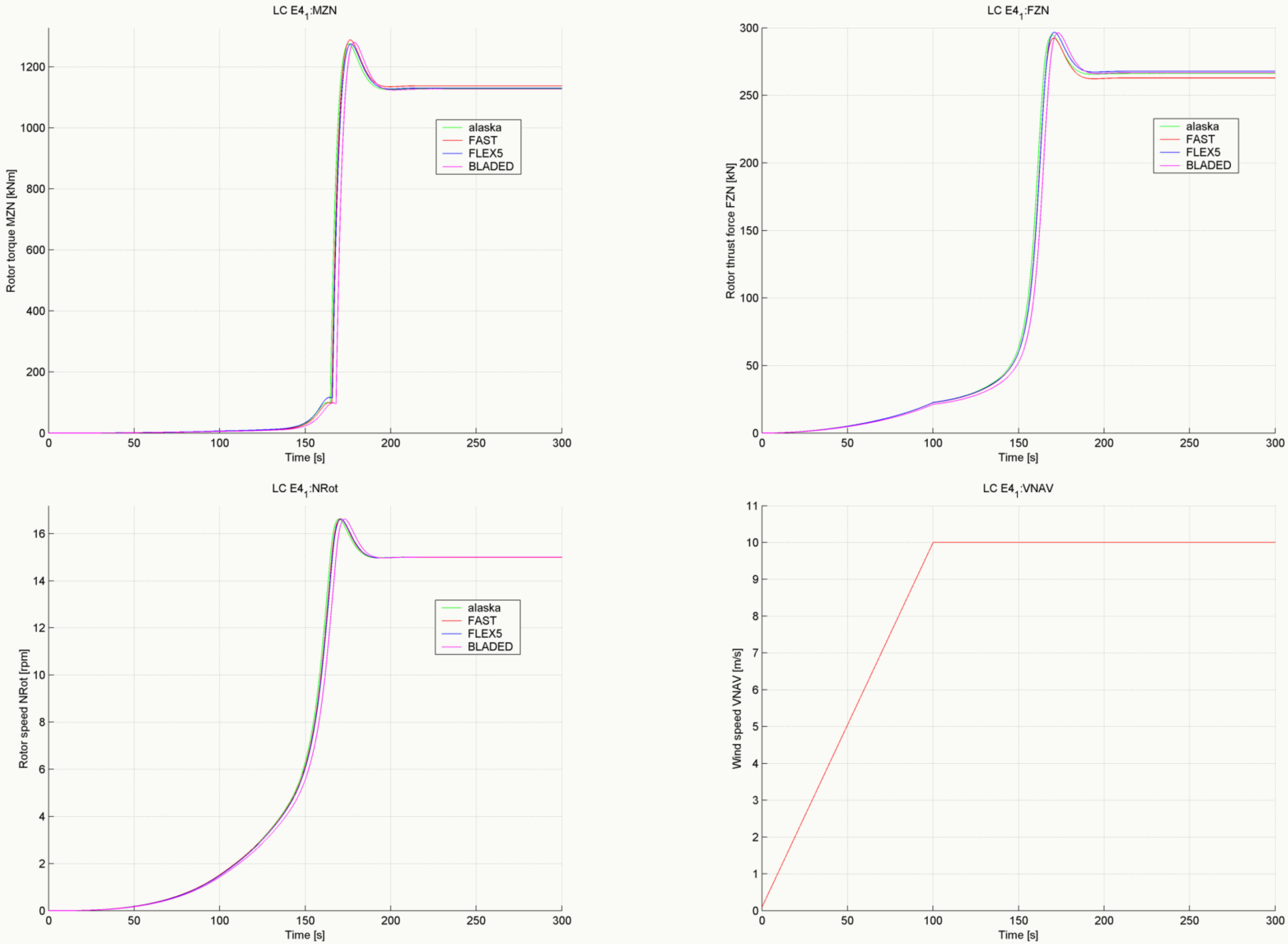
# Load Case LC E3, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible



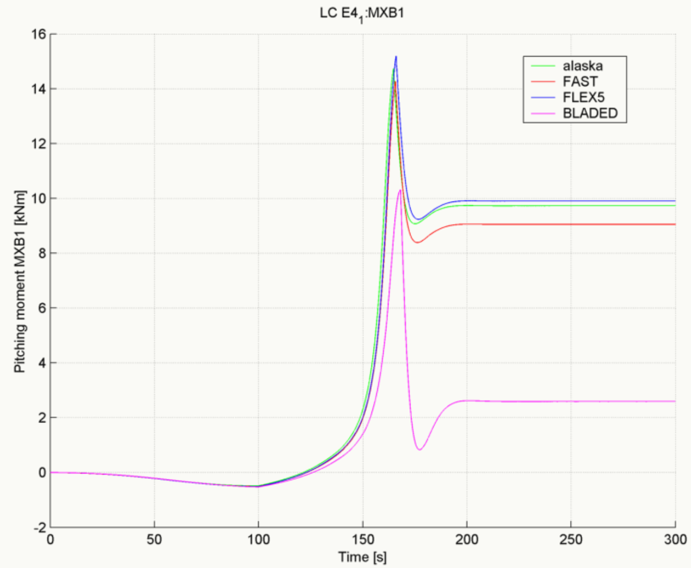



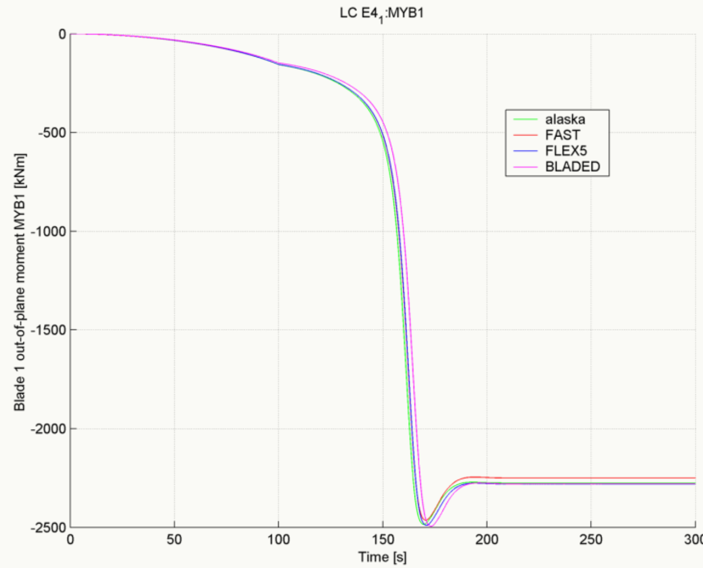
# Load Case LC E4_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

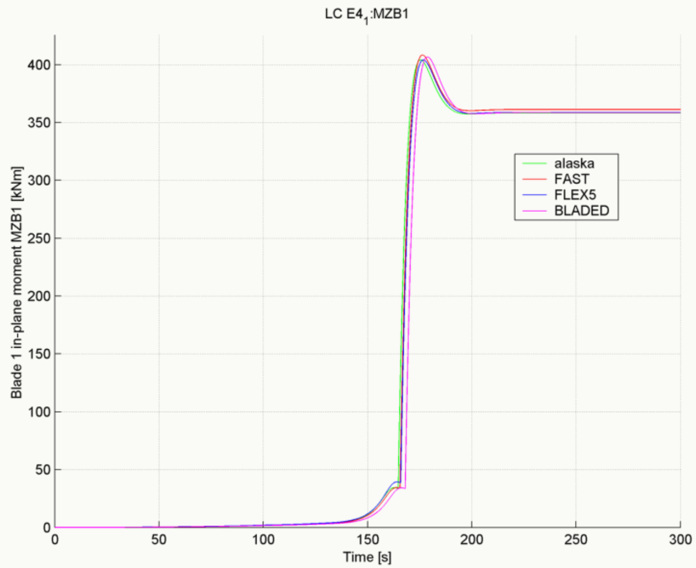




# Load Case LC E4_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible



# Load Case LC E4_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

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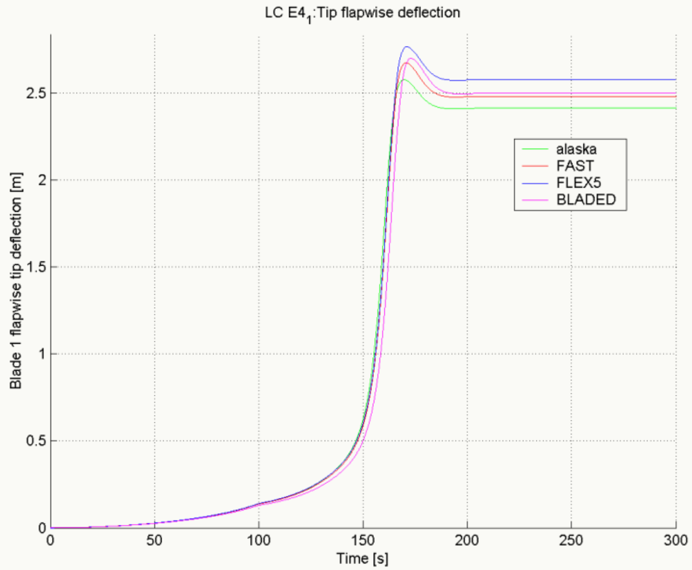
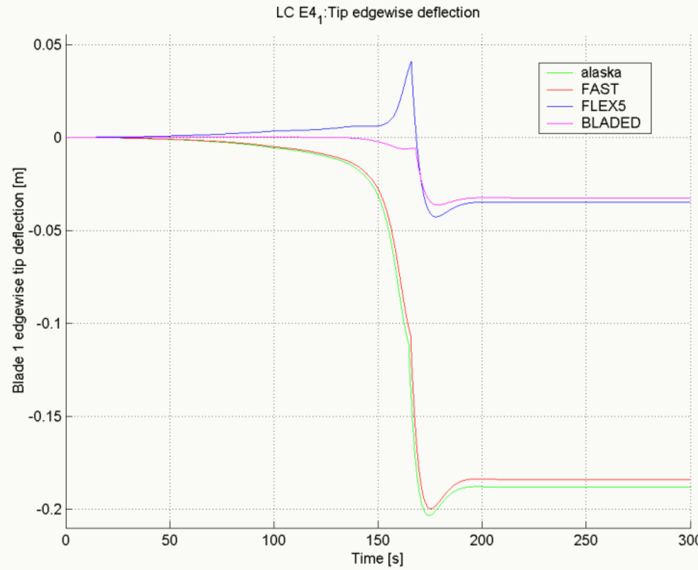


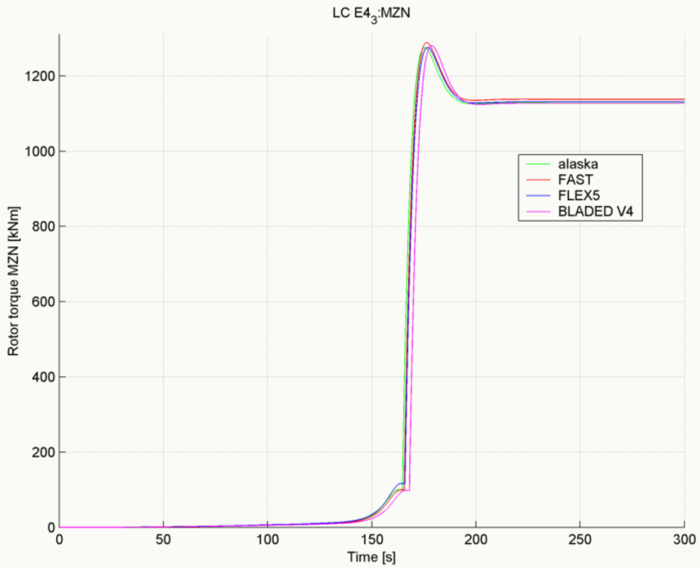



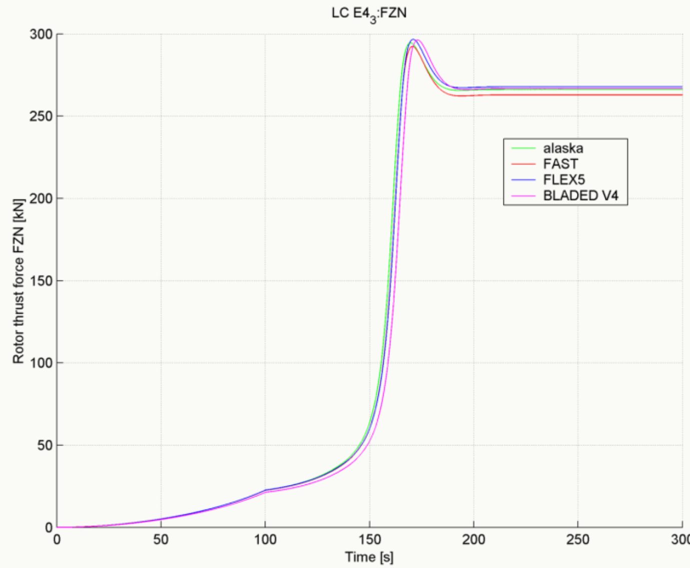
# Load Case LC E4_3, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

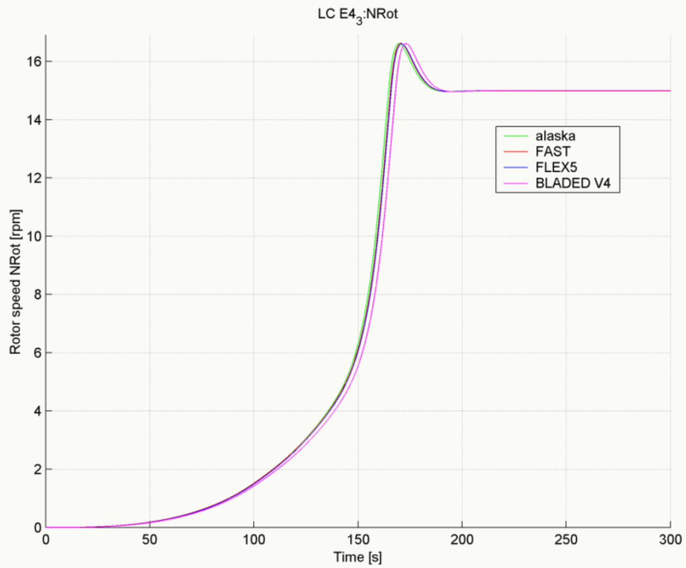
**The load case LC E4_3 is equivalent to load case LC E4_1 except that the new Multibody Dynamics BLADED V4 has been used instead of BLADED V3.82. Running load case LC E4_1 with BLADED V4 gave us the opportunity to investigate some of the recognized differences in the pitching moment and the edgewise tip deflection.**

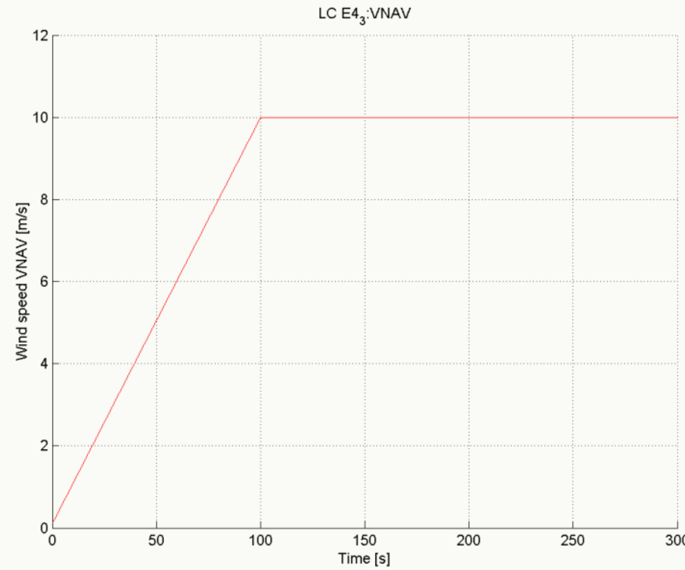
# Load Case LC E4_3, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

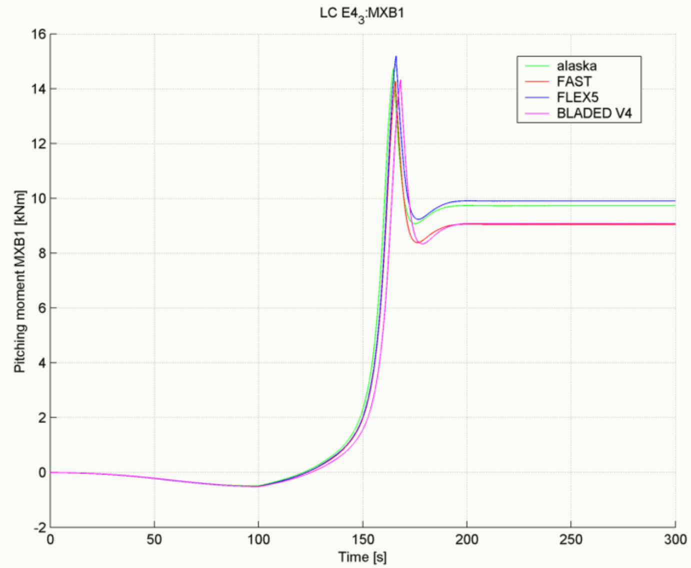


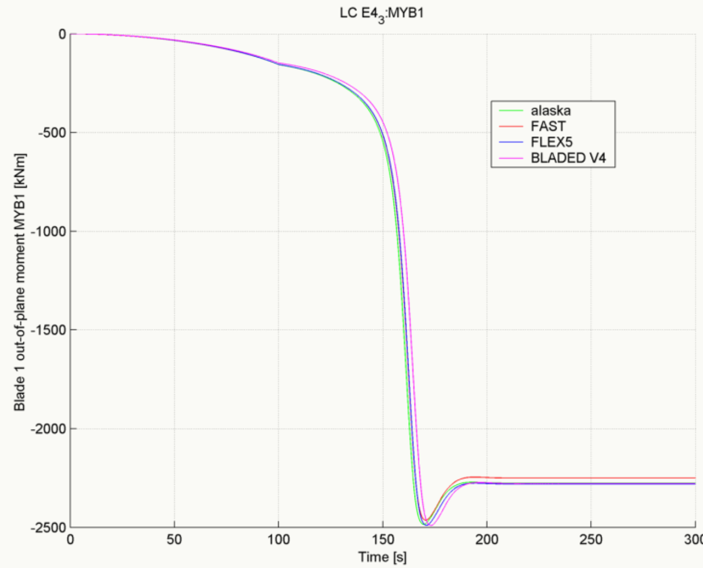


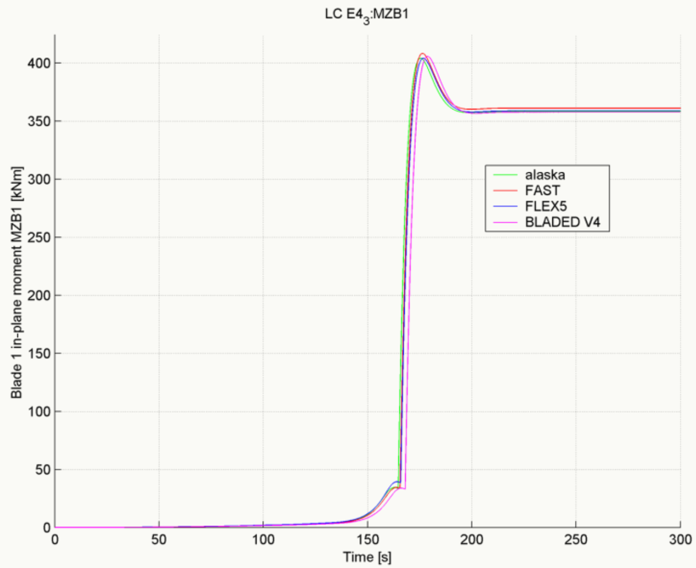



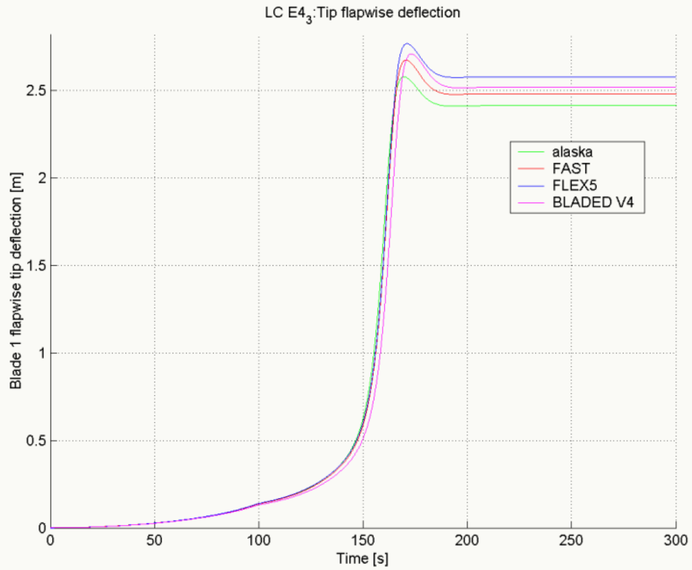



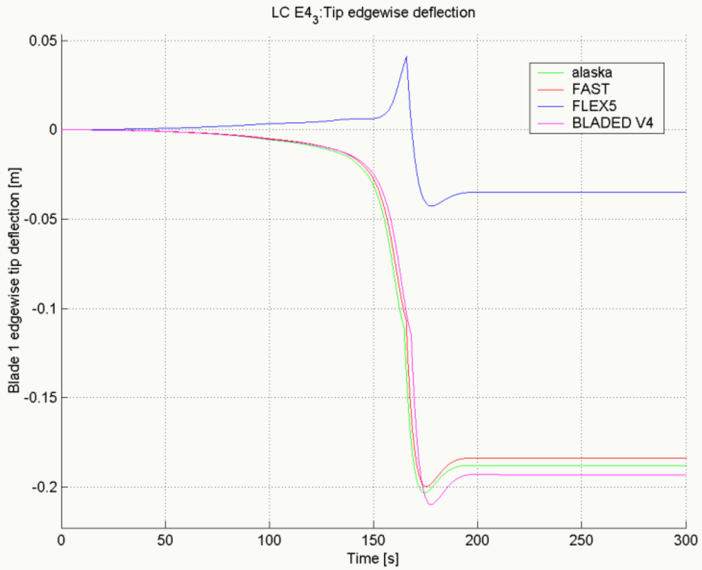

LC E4_3:MXB1
Pitching moment MXB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED V4


LC E4_3:MYB1
Blade 1 out-of-plane moment MYB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED V4

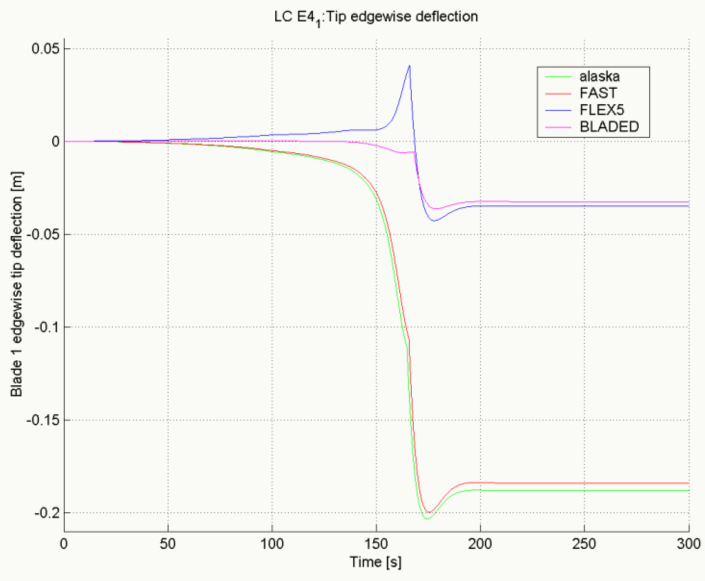

LC E4_3:MZB1
Blade 1 in-plane moment MZB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED V4

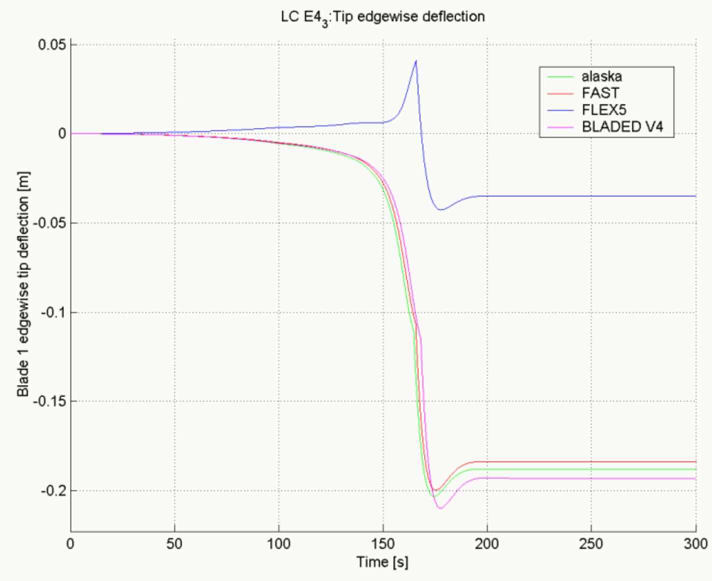


LC E4$_3$:Tip flapwise deflection
Blade 1 flapwise tip deflection [m]
0
0.5
1
1.5
2
2.5
0
50
100
150
200
250
300
Time [s]
alaska
FAST
FLEX5
BLADED V4

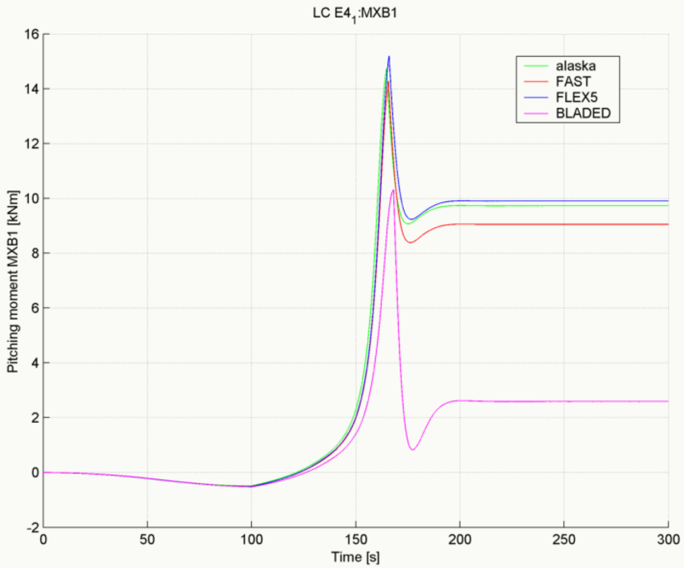



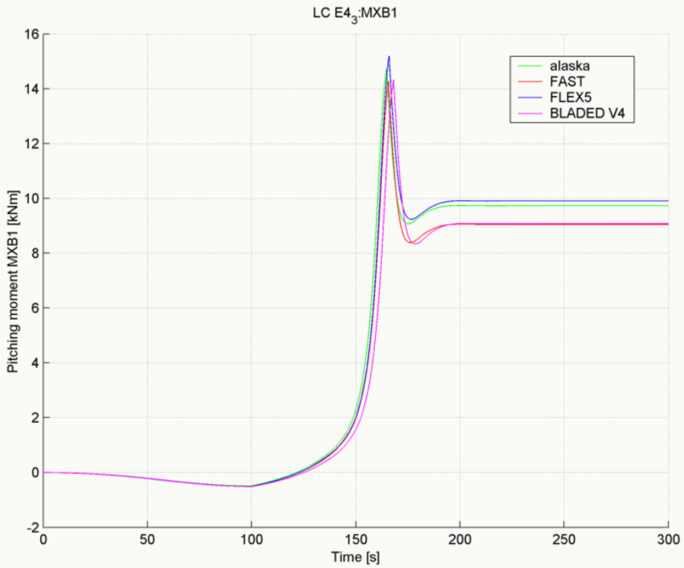
LC E4$_3$:Tip edgewise deflection
Blade 1 edgewise tip deflection [m]
0.05
0
-0.05
-0.1
-0.15
-0.2
0
50
100
150
200
250
300
Time [s]
alaska
FAST
FLEX5
BLADED V4




**Blade 1 edgewise tip deflection for BLADED V3.82 and BLADED V4**

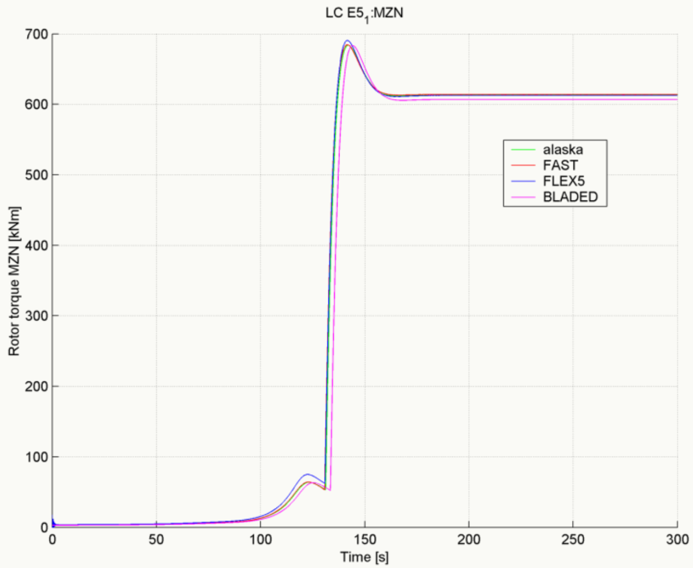


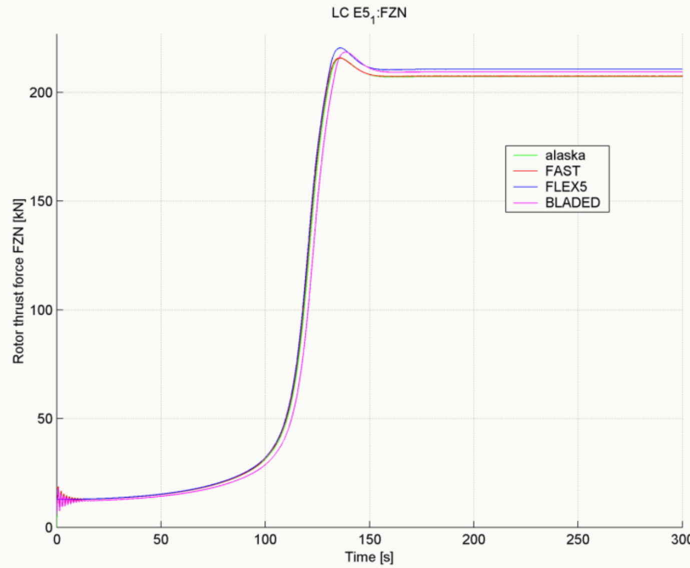



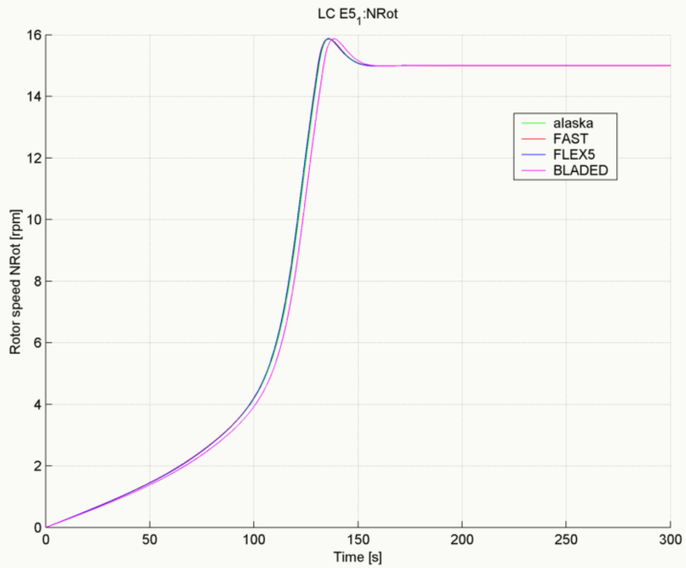

**Pitching moment for BLADED V3.82 and BLADED V4**

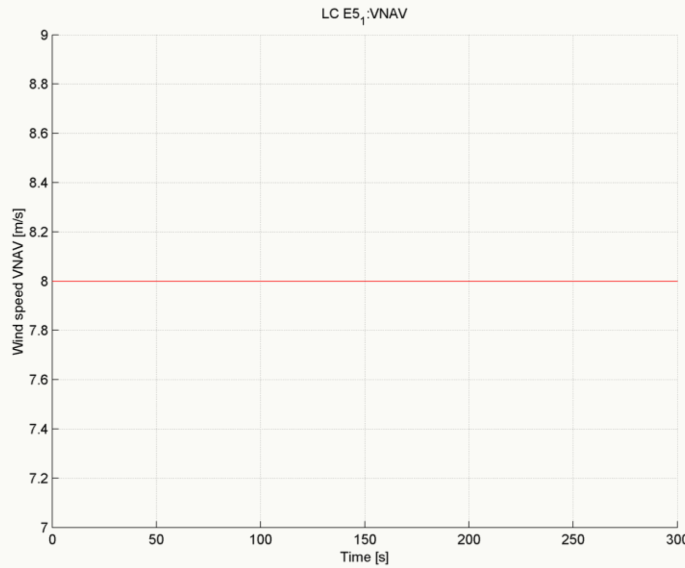
# Load Case LC E5_1, const. Wind = 8 m/s, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible





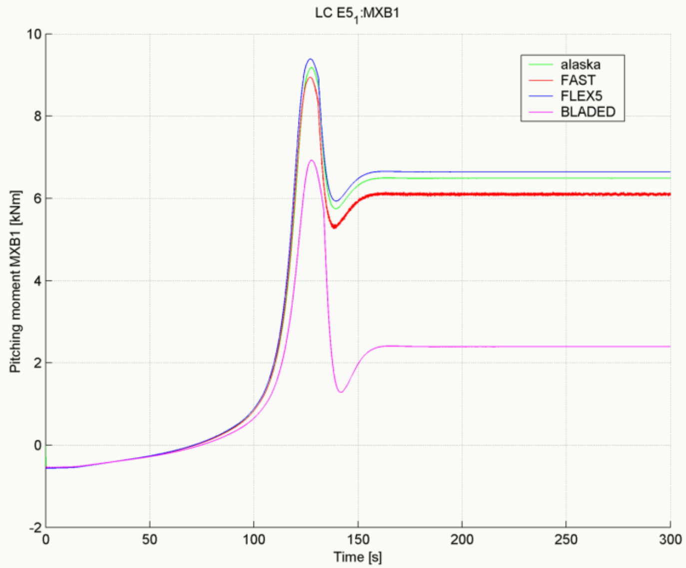



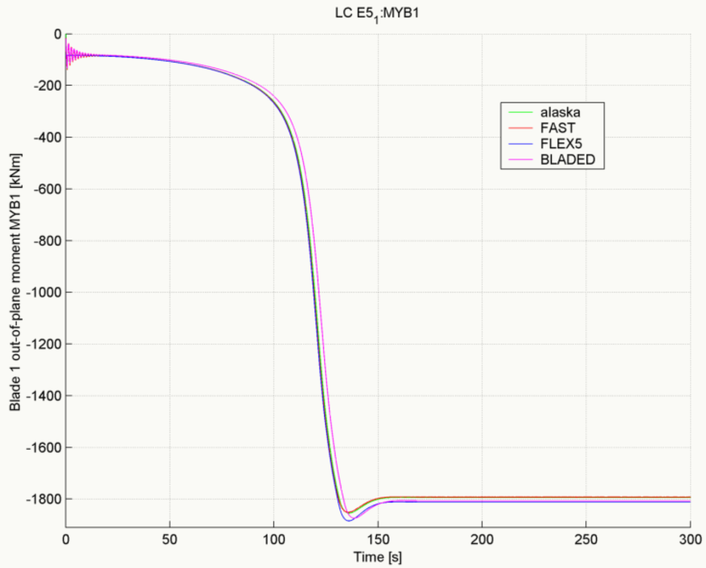



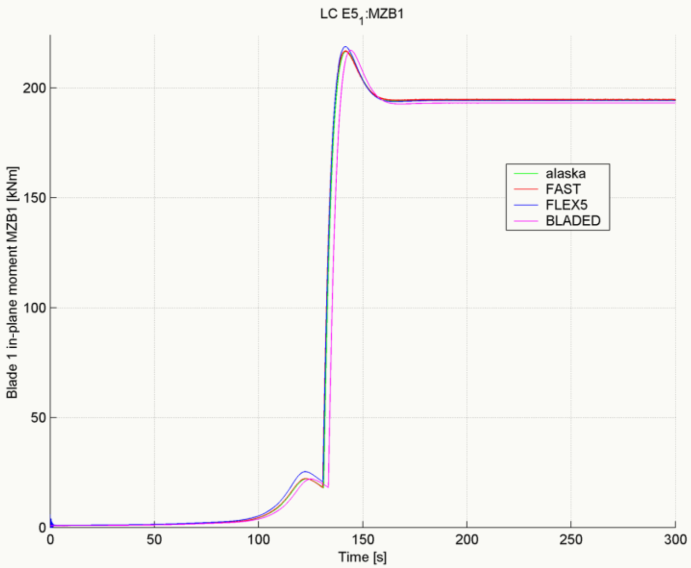



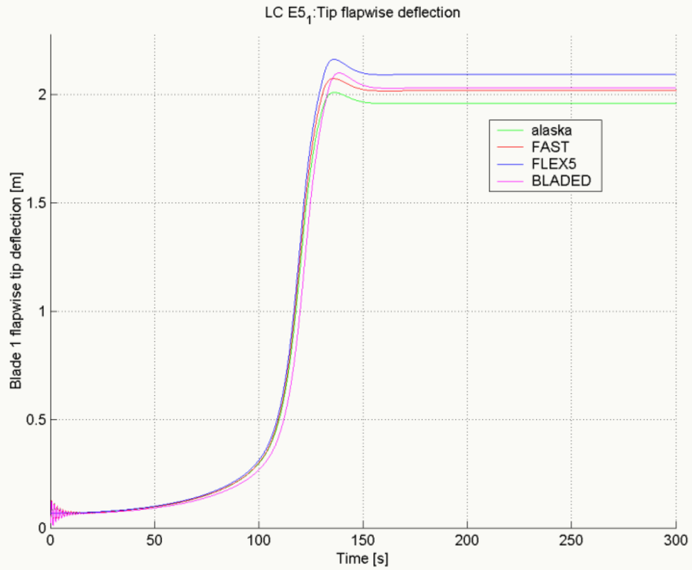
# Load Case LC E5_1, const. Wind = 8 m/s, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible



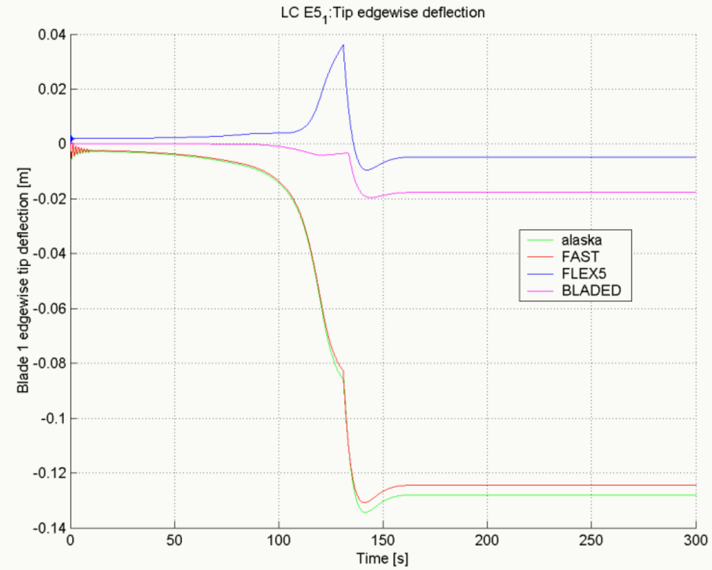




LC E5_1:Tip flapwise deflection
Blade 1 flapwise tip deflection [m]
Time [s]
alaska
FAST
FLEX5
BLADED

LC E5_1:Tip edgewise deflection
Blade 1 edgewise tip deflection [m]
Time [s]
alaska
FAST
FLEX5
BLADED

# Load Case LC E7_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

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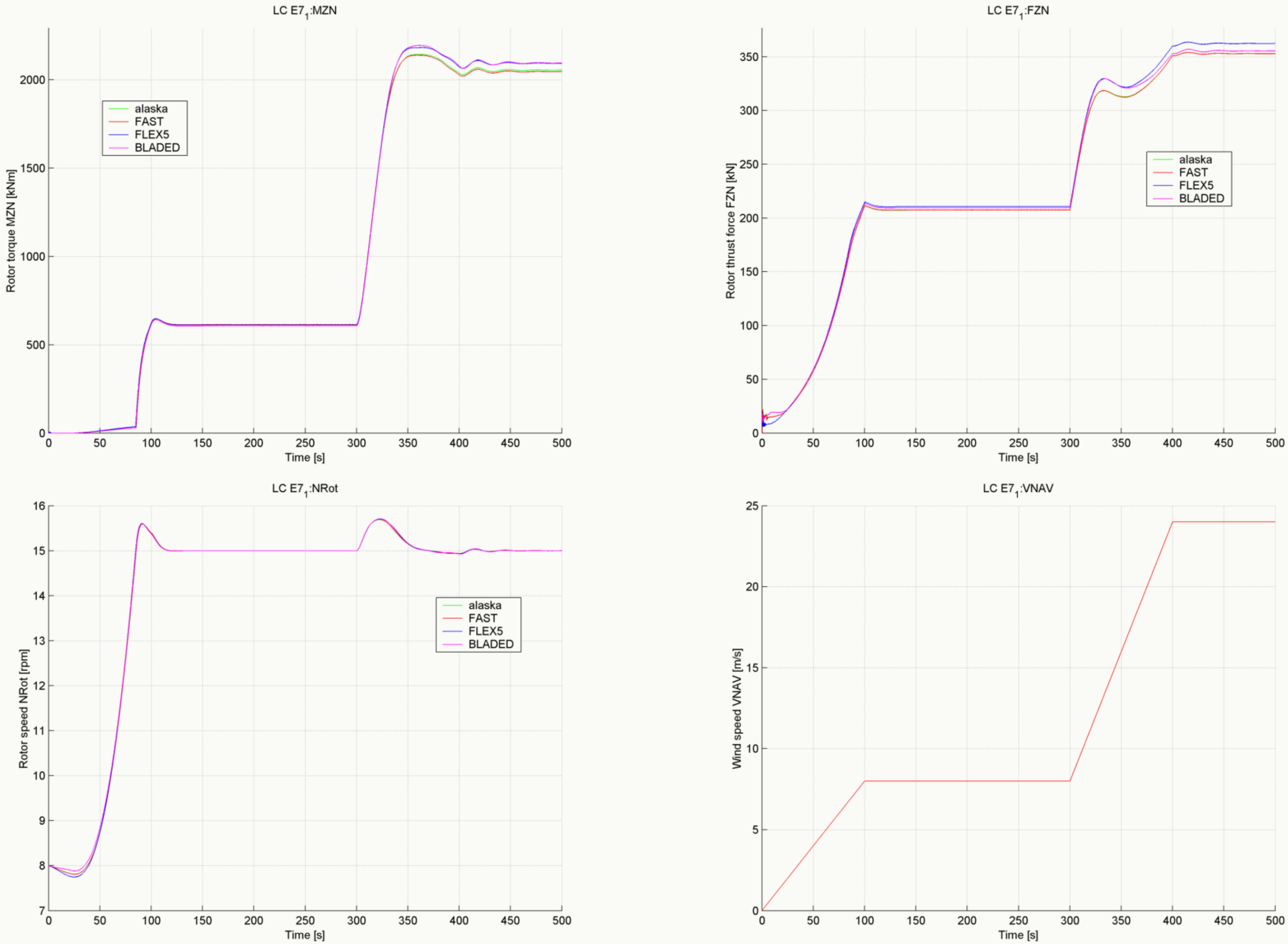
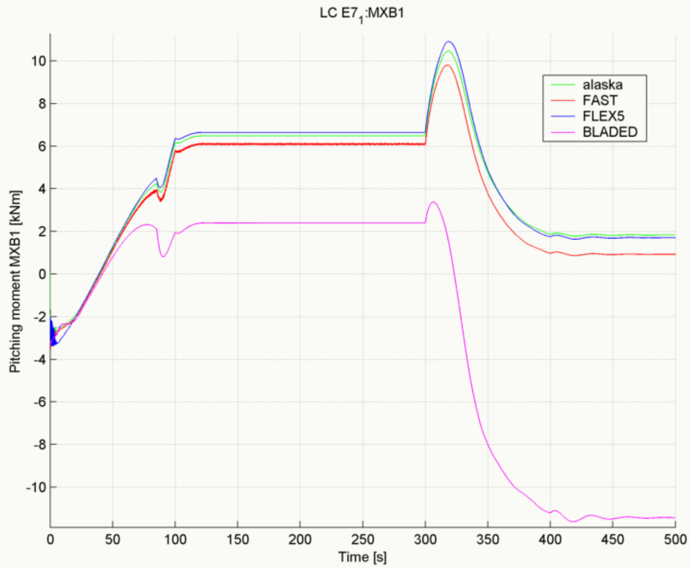
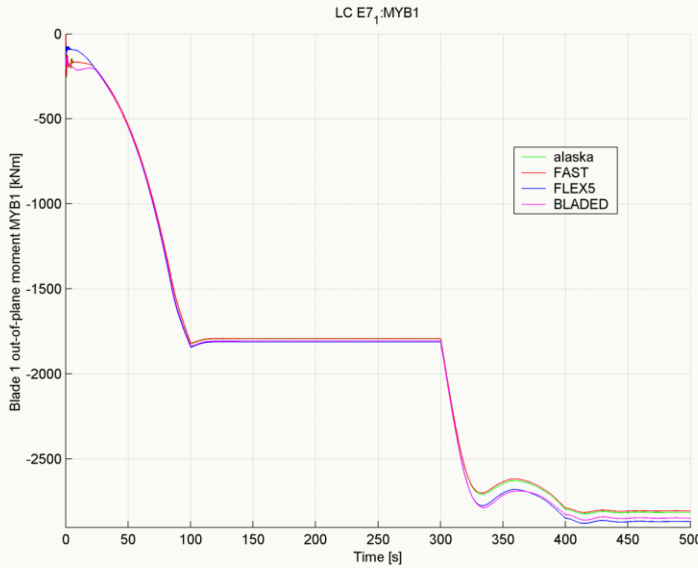
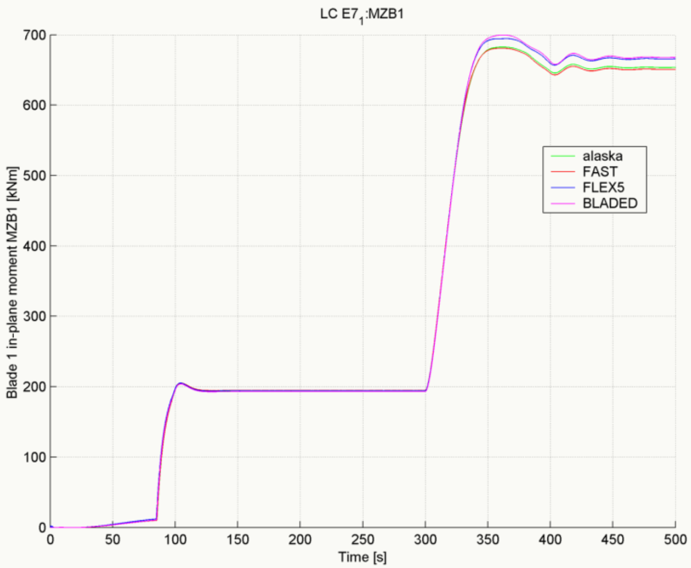


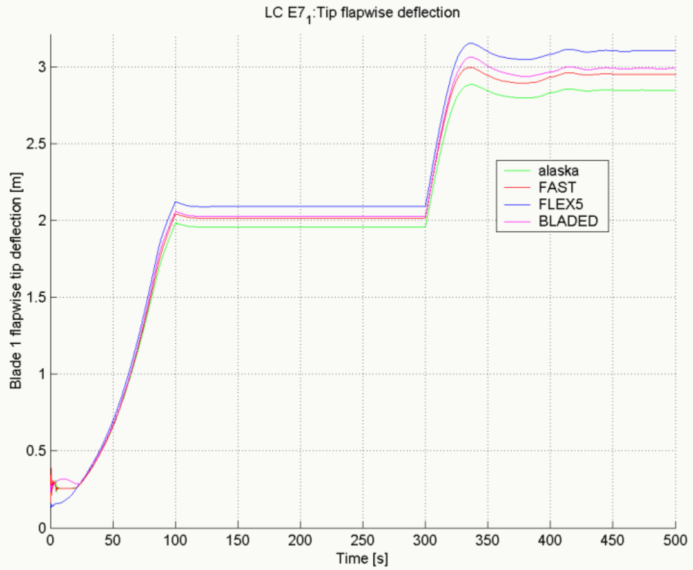

LC E7_1:MXB1
Pitching moment MXB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED

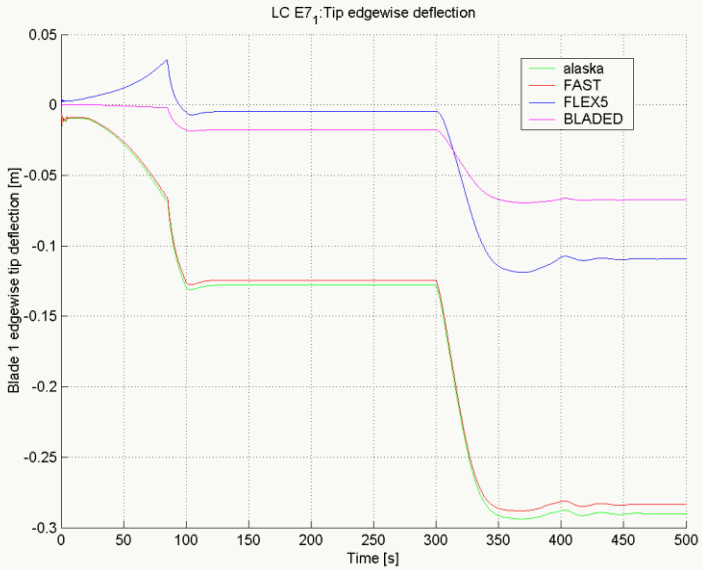

LC E7_1:MYB1
Blade 1 out-of-plane moment MYB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC E7_1:MZB1
Blade 1 in-plane moment MZB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED

# Load Case LC E7_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

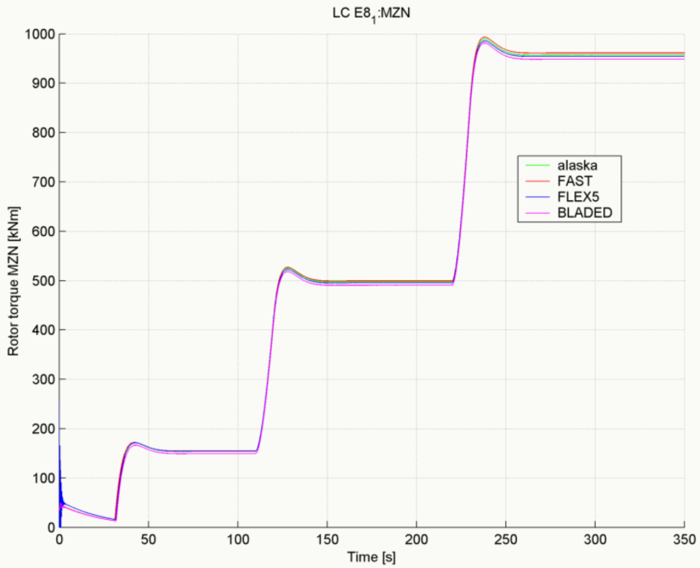


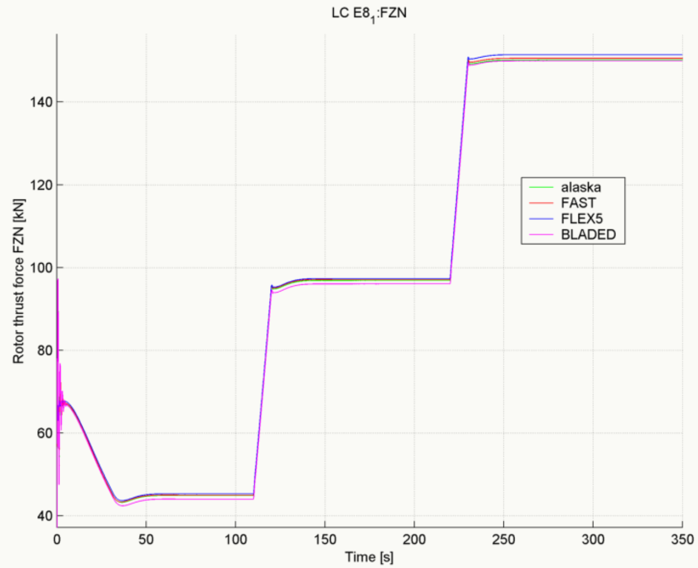


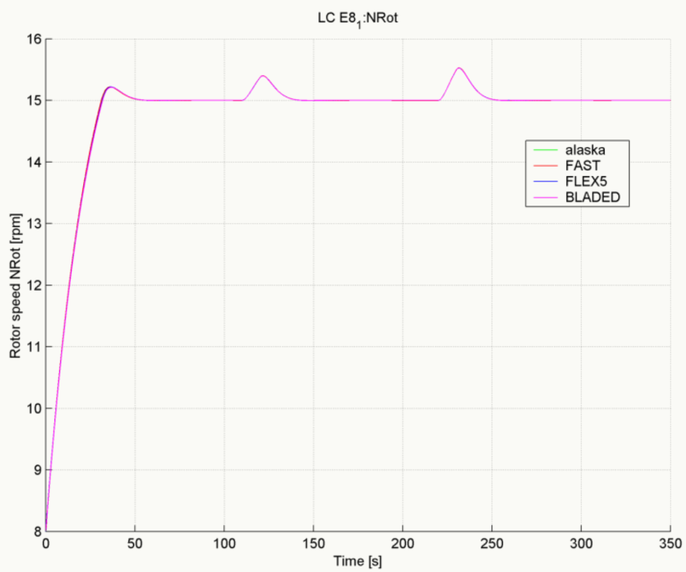



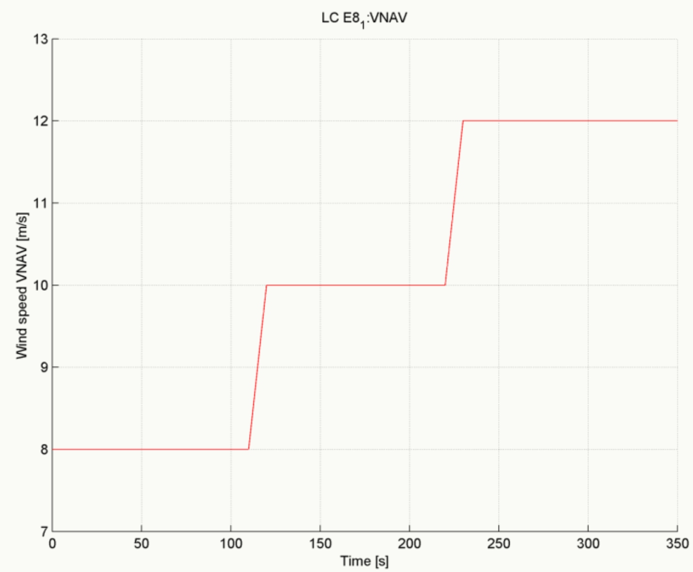
# Load Case LC E8_1, var. Wind, Rotor stationary 15 rpm, Pitch fixed 10°, Yaw fixed 0°, Rotor Blades flexible

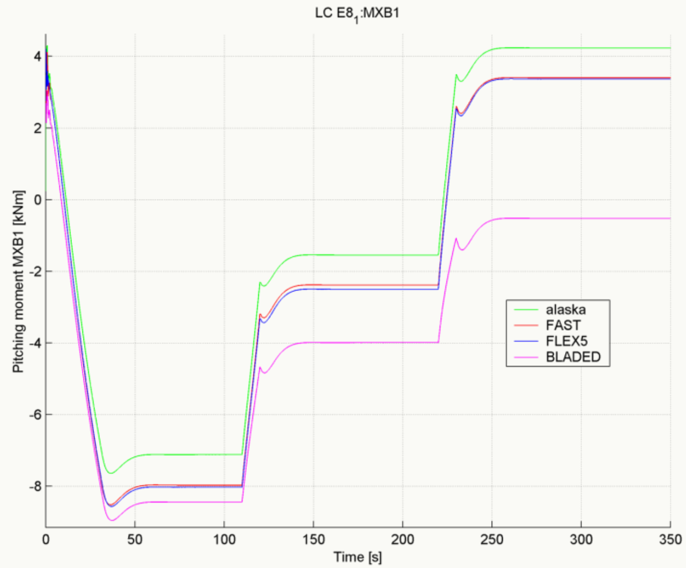


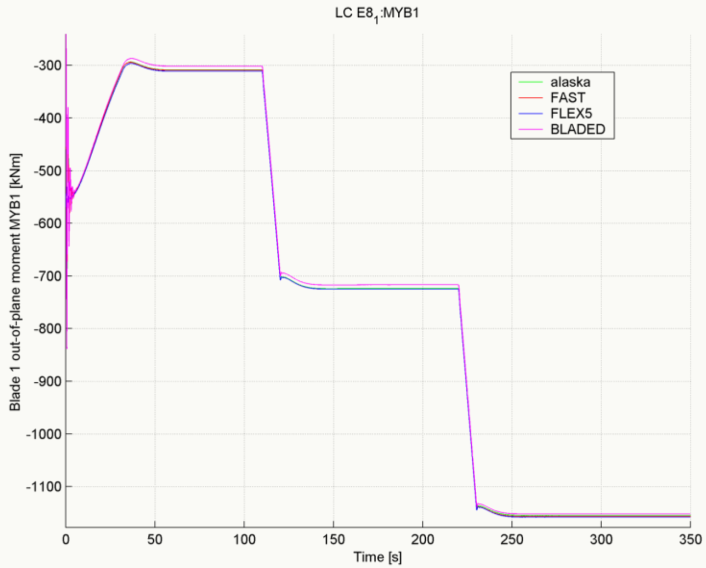


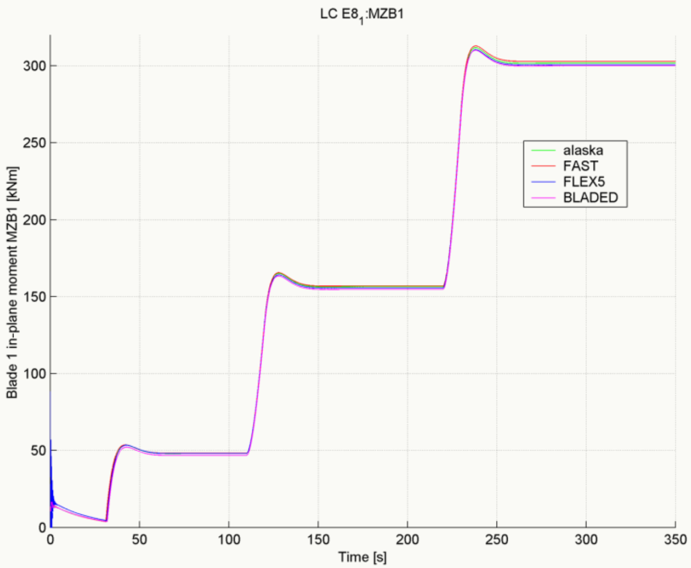



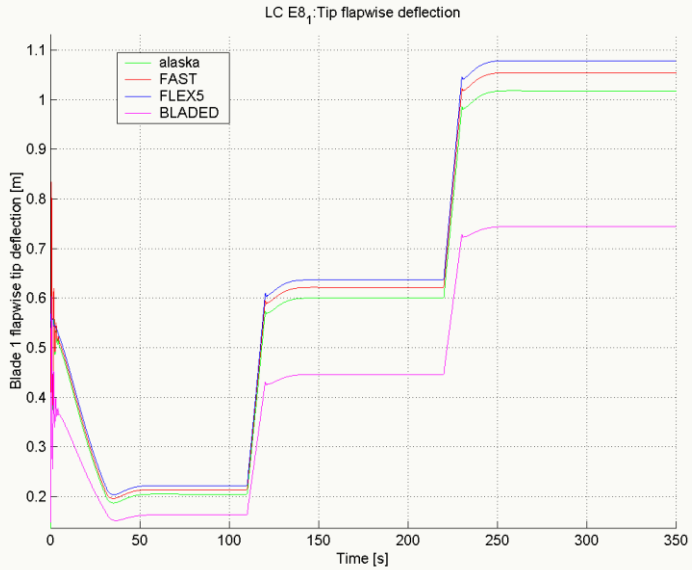



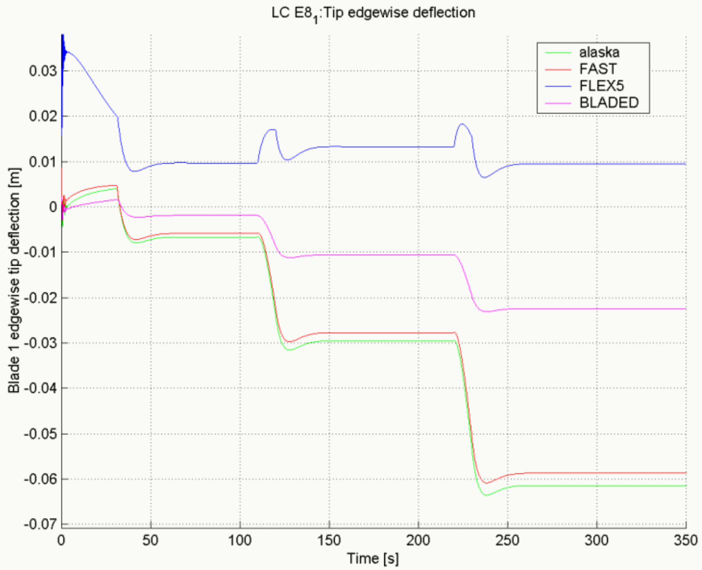




LC E8$_1$:MXB1
Pitching moment MXB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC E8$_1$:MYB1
Blade 1 out-of-plane moment MYB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC E8$_1$:MZB1
Blade 1 in-plane moment MZB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC E8_1:Tip flapwise deflection
Blade 1 flapwise tip deflection [m]
Time [s]
alaska
FAST
FLEX5
BLADED


LC E8_1:Tip edgewise deflection
Blade 1 edgewise tip deflection [m]
Time [s]
alaska
FAST
FLEX5
BLADED

# Load Case LC E15, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Tower flexible

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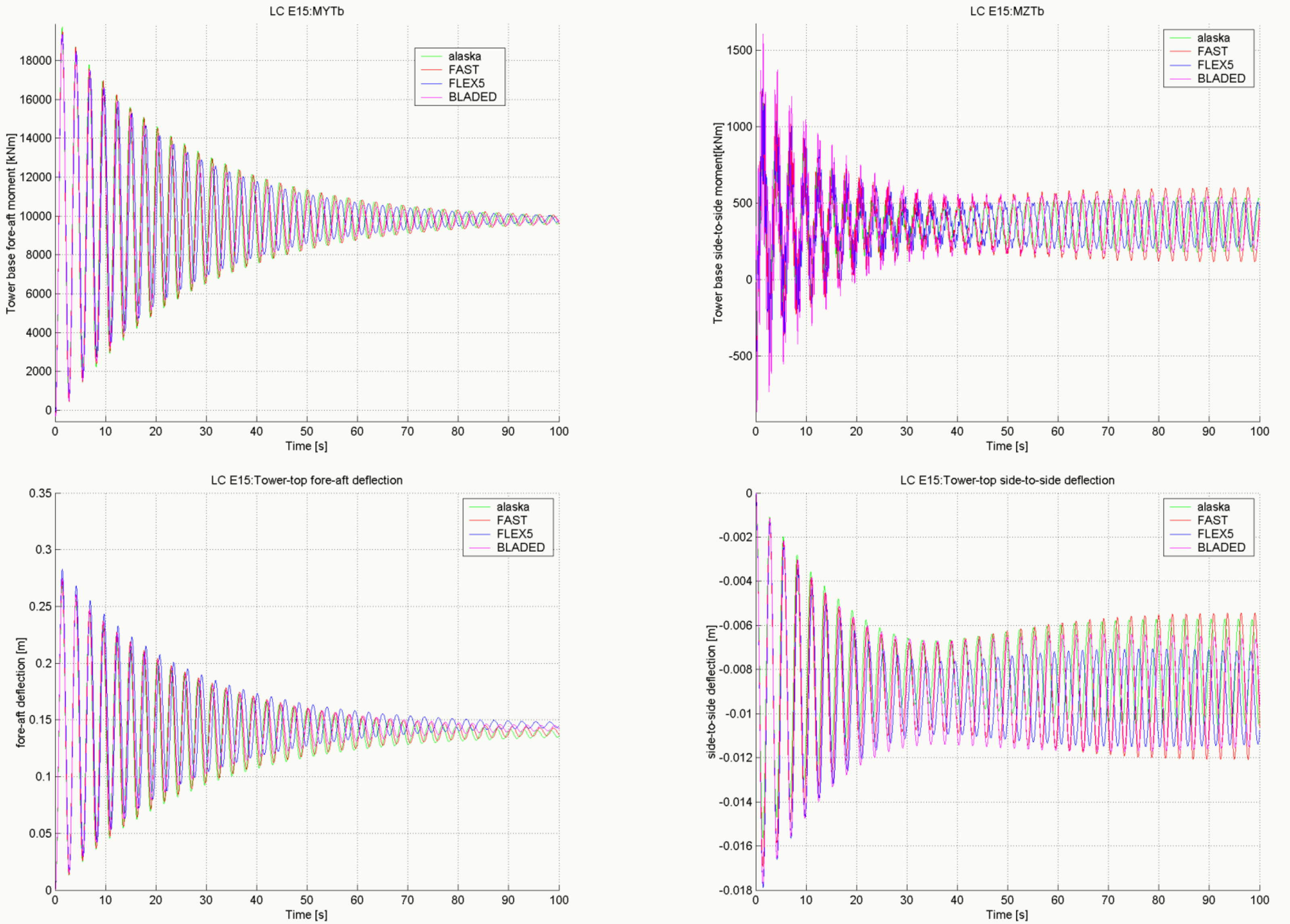
**The load case LC E15 has been used for validating the modal tower model in connection with the turbine model. For this load case, the turbine model has been parked and all degree of freedom are locked except the tower modes. At the beginning of the simulation, a tower vibration has been induced by a gust of wind.**

# Load Case LC E15, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Tower flexible





# Load Case LC E15, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Tower flexible

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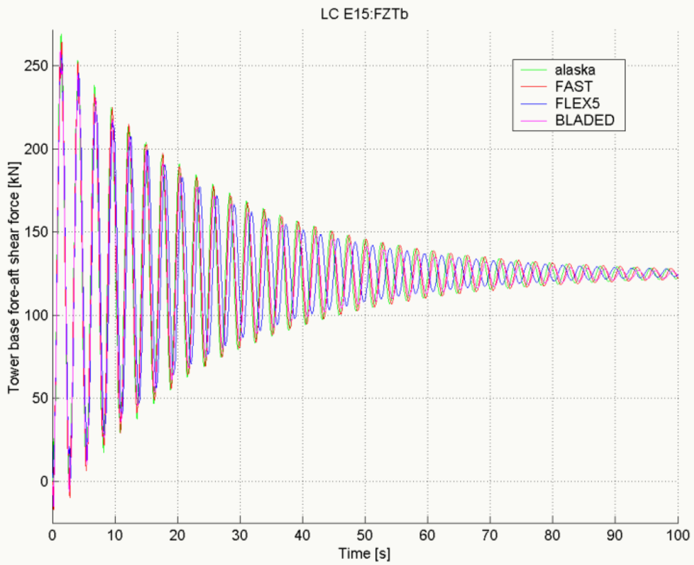
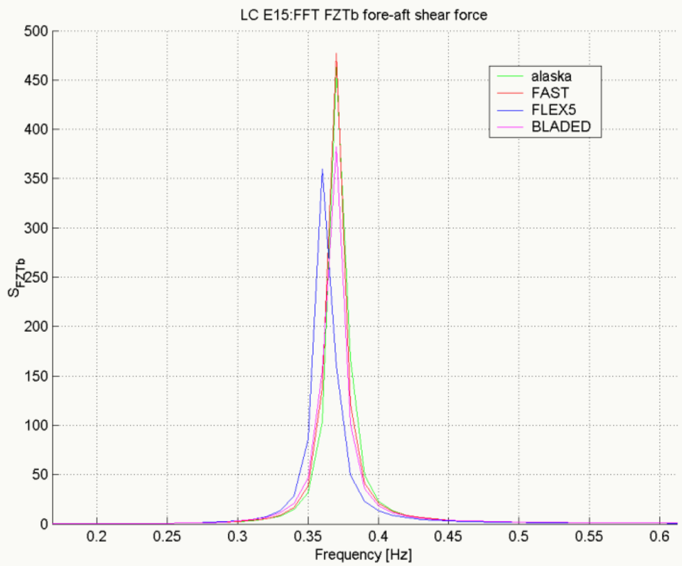
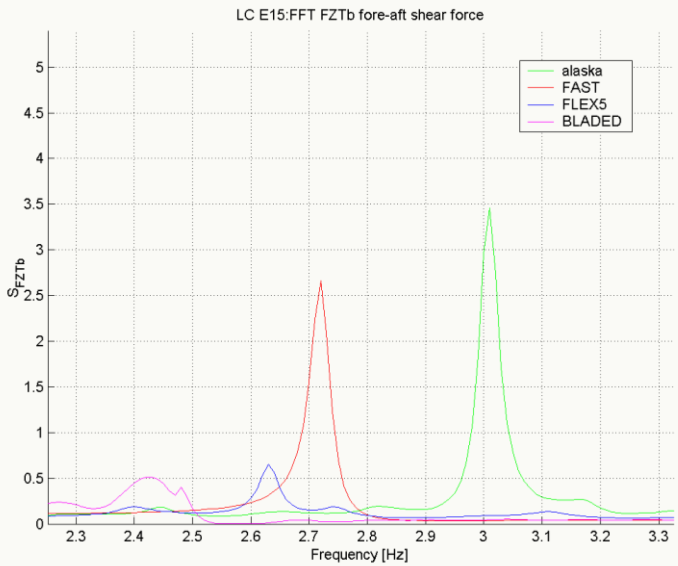
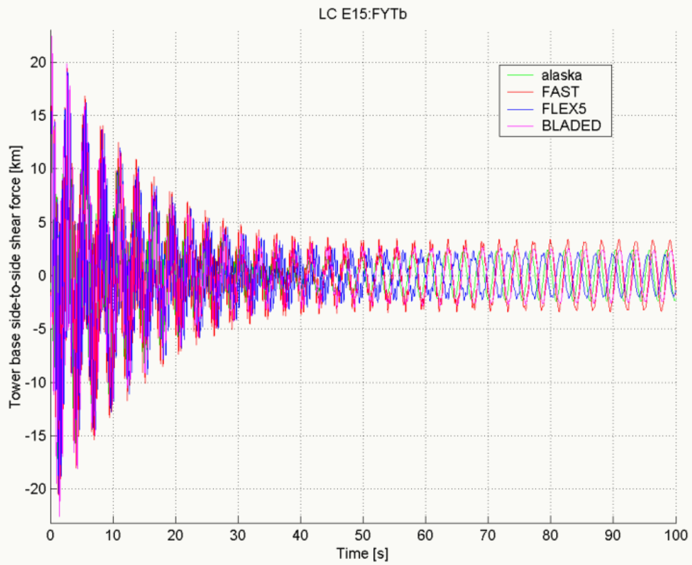


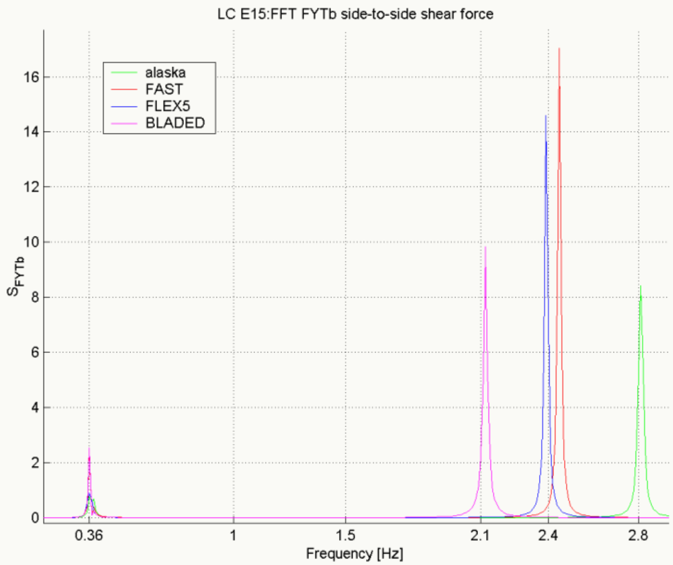



# Load Case LC E15, var. Wind, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Tower flexible





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## LCGroup I_Turb

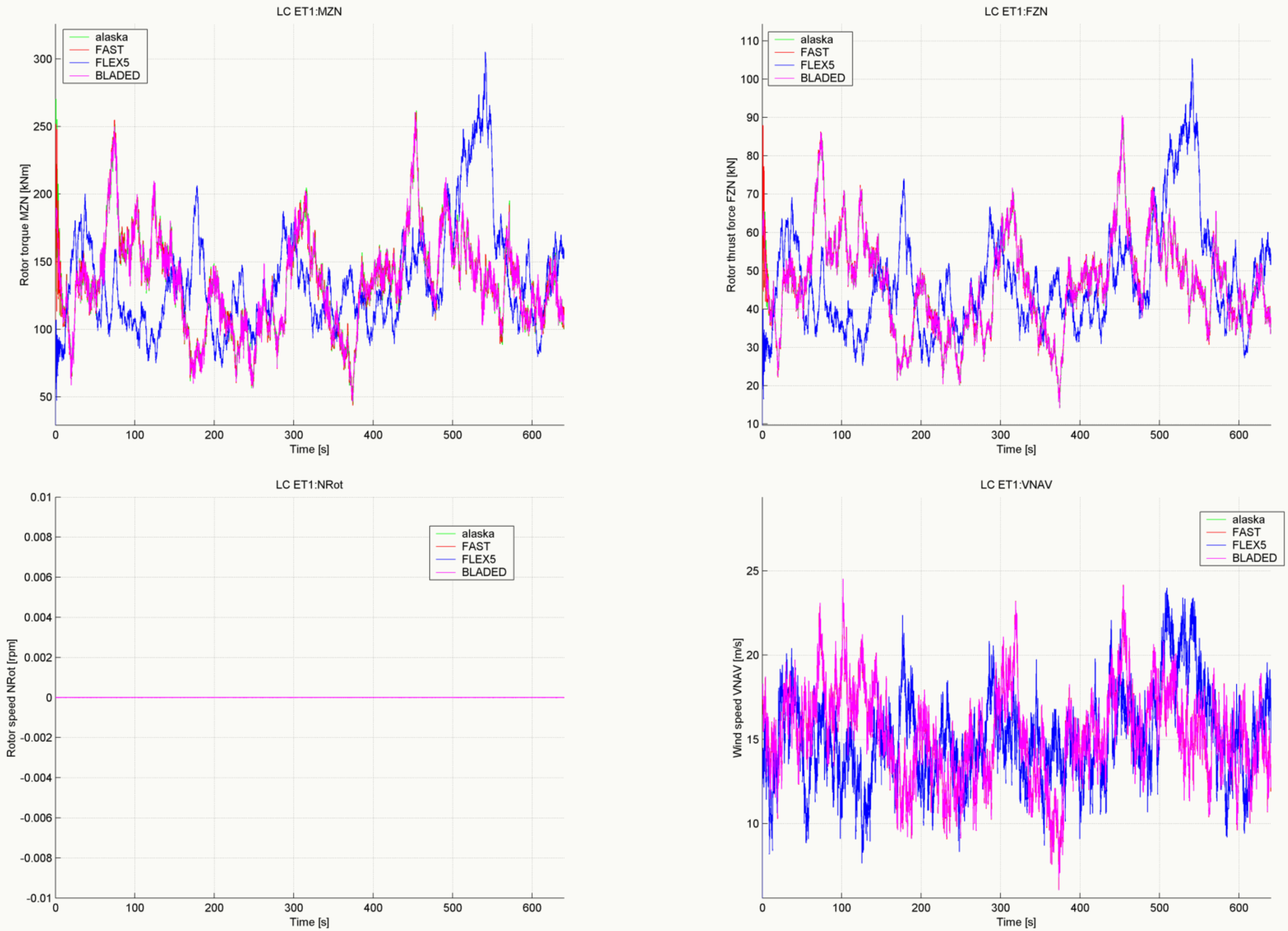
| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Blade DOF 2 Flap, 1 Edge | Pitch | Yaw | Rotor IC | Generator / Motor | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | EqI/GDW | None/ Bed/Oye | on/off | on/off | None/Log/Exp | [s] | on/off | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | const/var [m/s] | const/var | [on/off] | [s] | [s] |
| ET1 | EqI | None | on | off | None | 0.02 | off | off | on | fixed, 0° | fixed, 0° | 0 | off | var1 | 0° | on | 0,02 | 640 |
| T2 | EqI | None | on | off | None | 0.02 | off | on | off | fixed, 30° | fixed, 0° | 11 | off | var1 | 0° | on | 0,02 | 640 |
| ET2 | EqI | None | on | off | None | 0.02 | off | on | on | fixed, 30° | fixed, 0° | 11 | off | var1 | 0° | on | 0,02 | 640 |

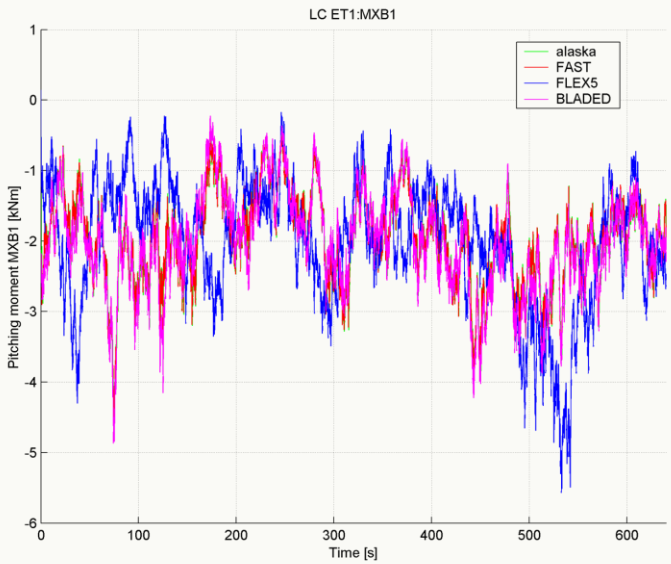
- **wind shear off**
- **tower shadow off**
- **flexible blade model**
- **turbulent wind**

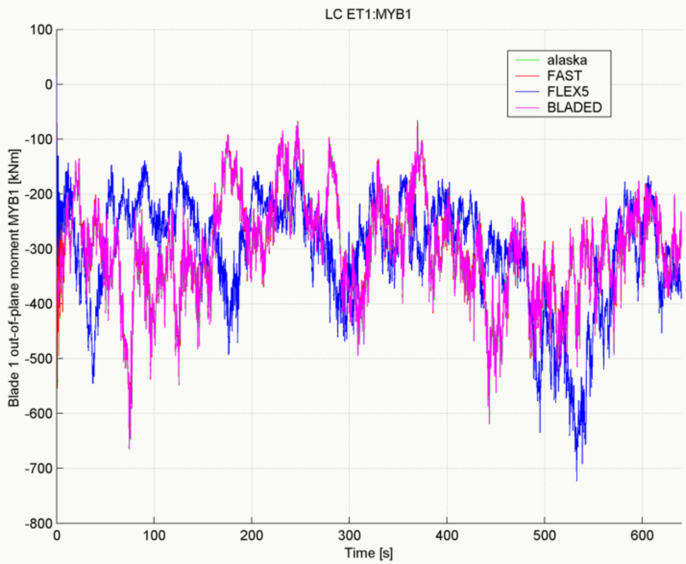
**In LCGroup I_Turb, the wind turbine operates under turbulent wind conditions. The necessary full-field turbulent wind has been generated by TurbSim [2] using IEC Kaimal spectral model. TurbSim allows the generation of BLADED-style turbulence files which are also able to be used in alaska/Wind and FAST. FLEX5 uses a polar turbulence format instead of a rectangular format for the turbulence field description. For the FLEX5 model, a sepearate polar turbulence field based on IEC Kaimal spectral model has been generated using Vindsim7. The validation of the turbulence wind field has been carried out in load case LC T1 from load case group LCGroup I_TurbSim (page 119).**

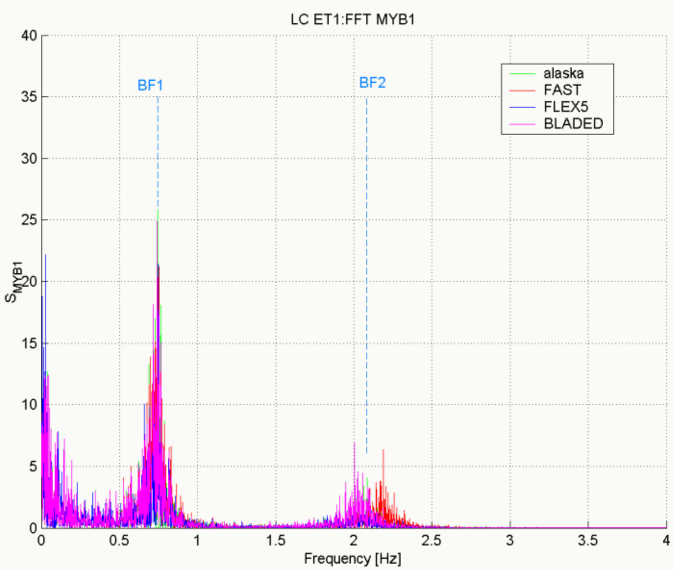
# Load Case LC ET1, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible

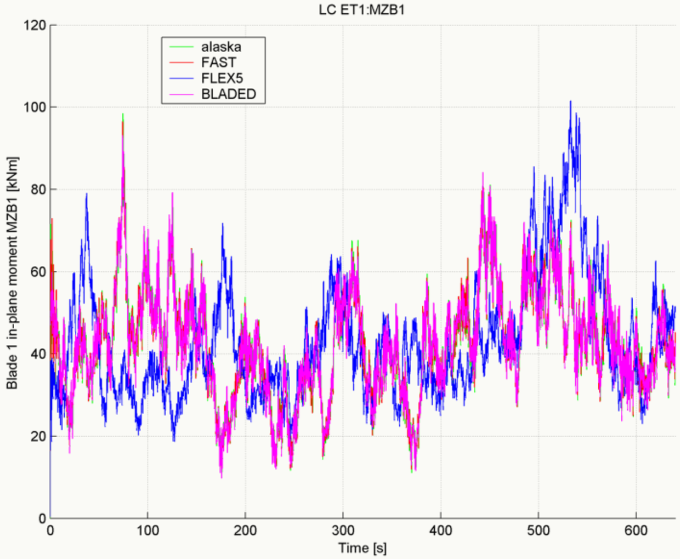


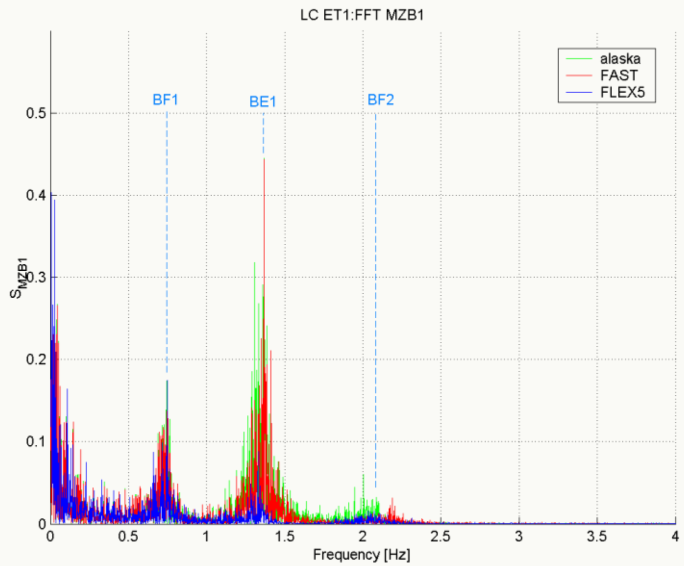


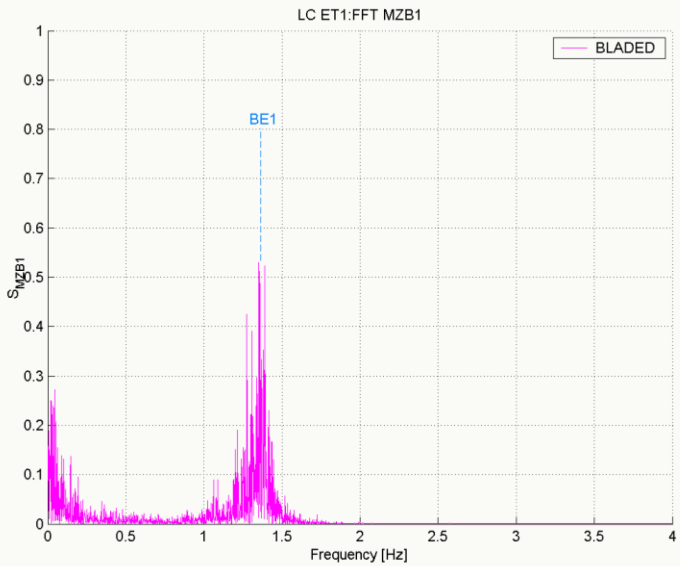

LC ET1:MXB1
Pitching moment MXB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC ET1:MYB1
Blade 1 out-of-plane moment MYB1 [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC ET1:FFT MYB1
BF1
BF2
Frequency [Hz]
alaska
FAST
FLEX5
BLADED

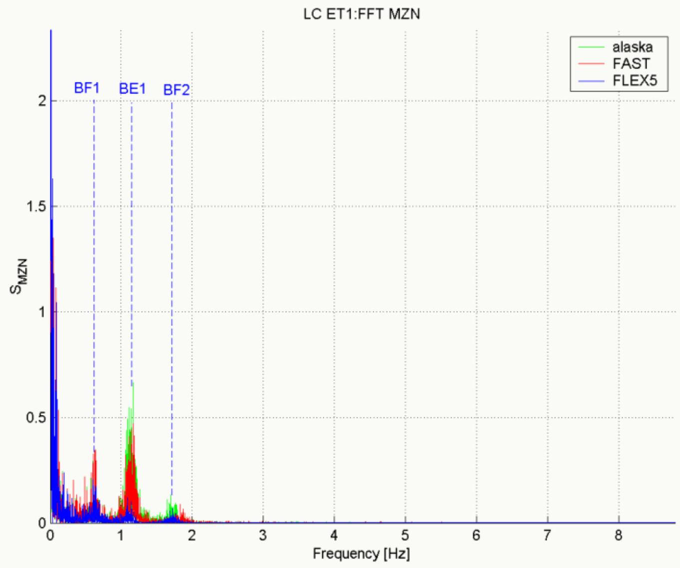

LC ET1:MZB1
alaska
FAST
FLEX5
BLADED
Blade 1 in-plane moment MZB1 [kNm]
Time [s]

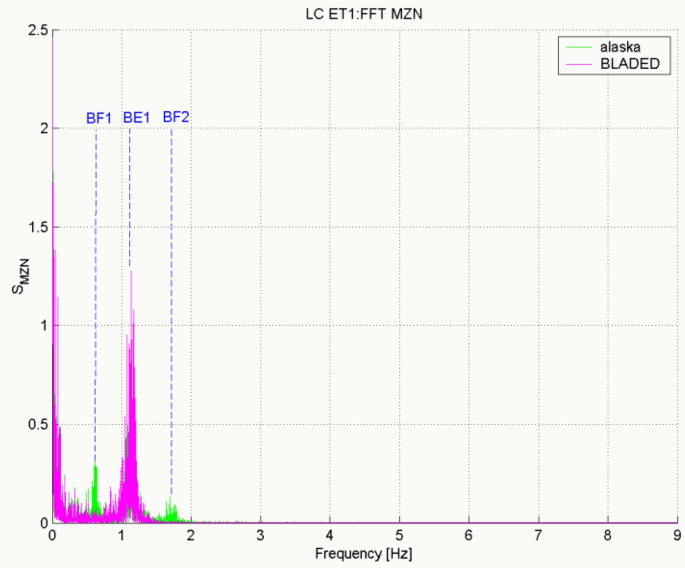

LC ET1:FFT MZB1
alaska
FAST
FLEX5
BF1
BE1
BF2
S MZB1
Frequency [Hz]


LC ET1:FFT MZB1
BLADED
BE1
S MZB1
Frequency [Hz]

# Load Case LC ET1, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible





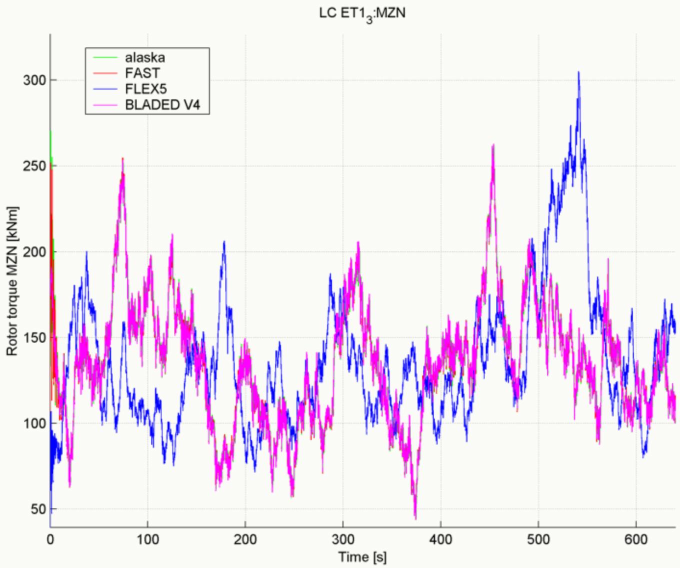
# Load Case LC ET1_3, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

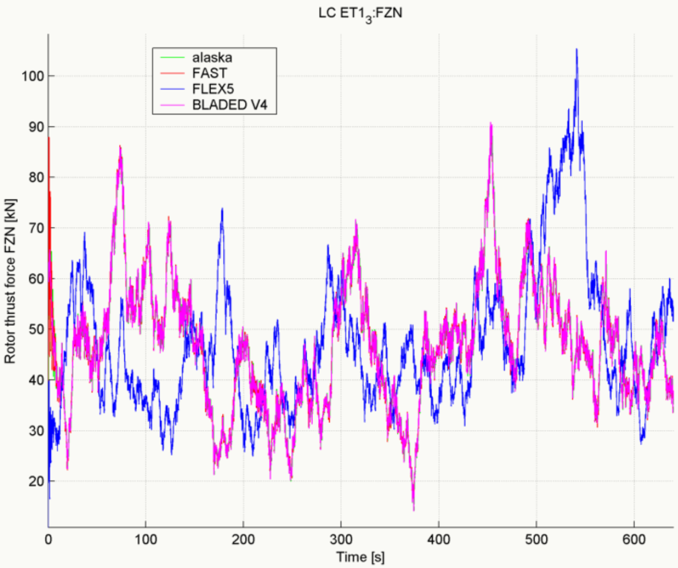


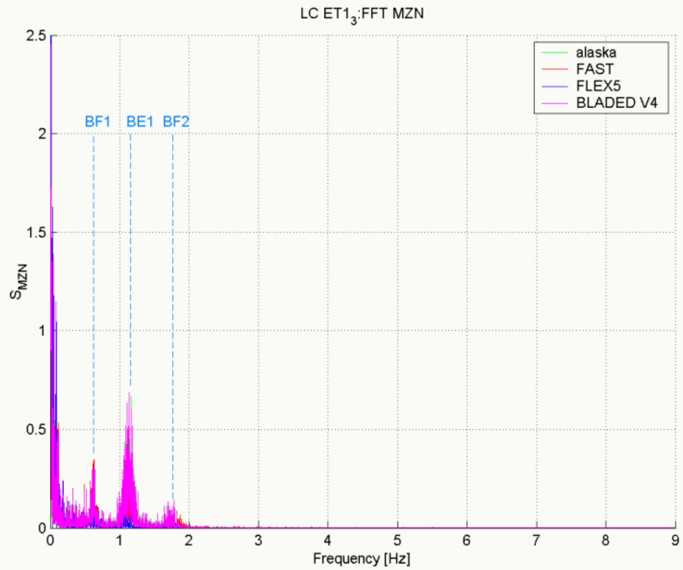
**The load case LC ET1_3 is equivalent to load case LC ET1 except that the new Multibody Dynamics BLADED V4 has been used instead of BLADED V3.82.**

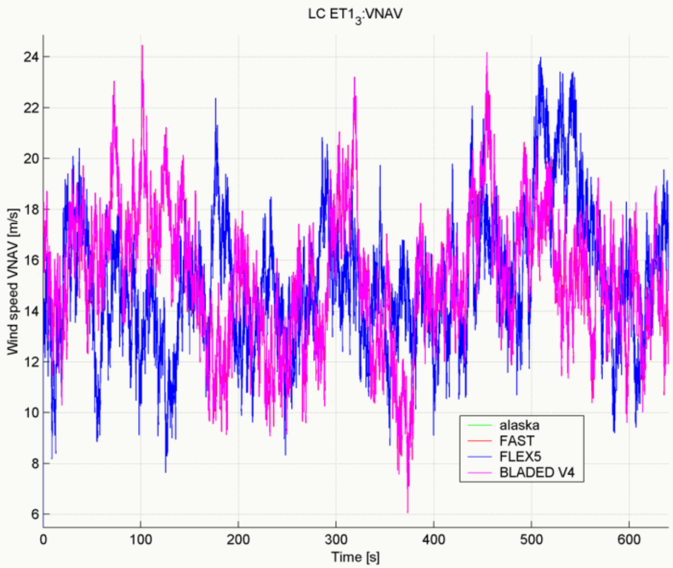
# Load Case LC ET1_3, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4



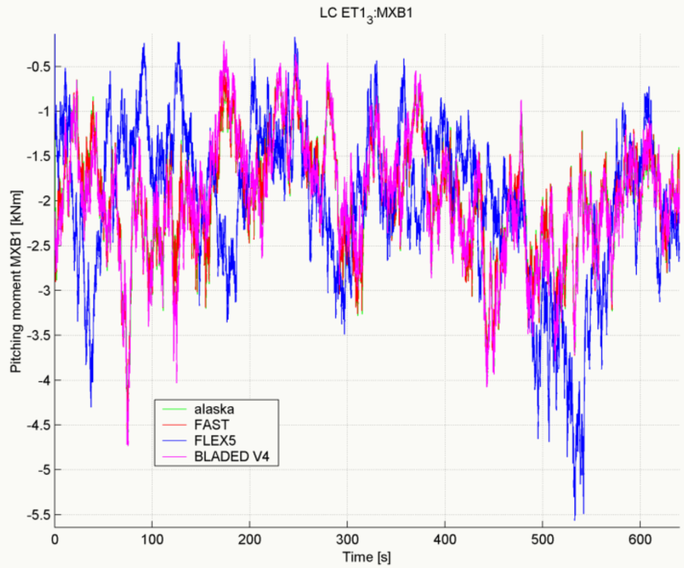


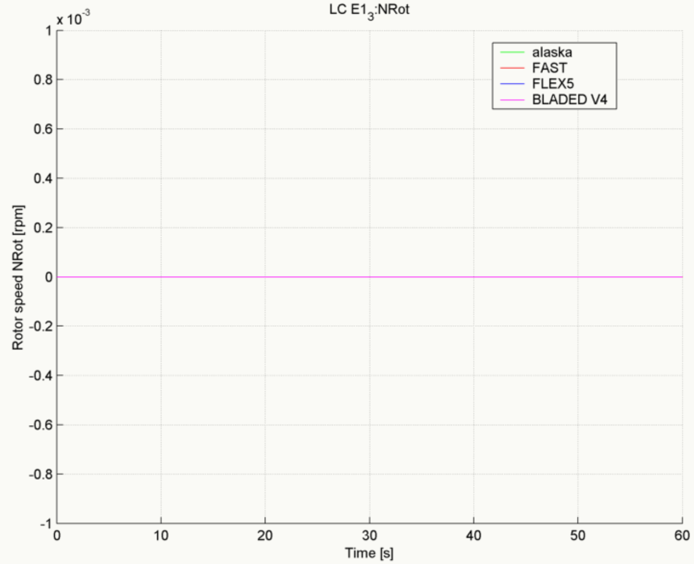



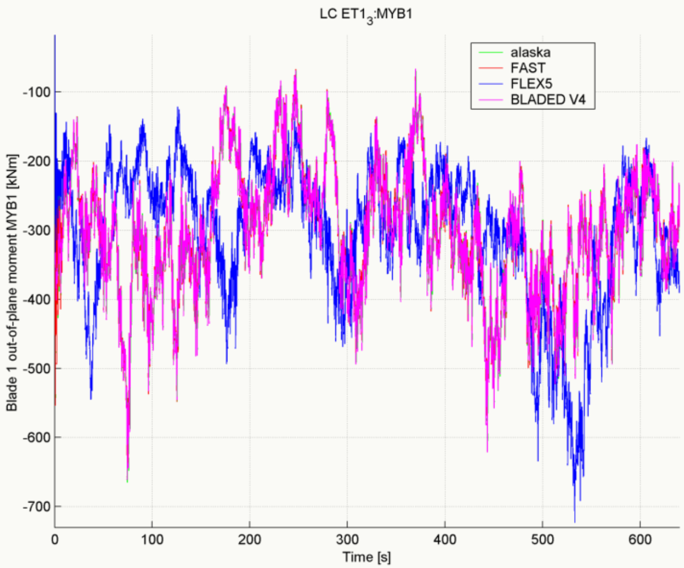



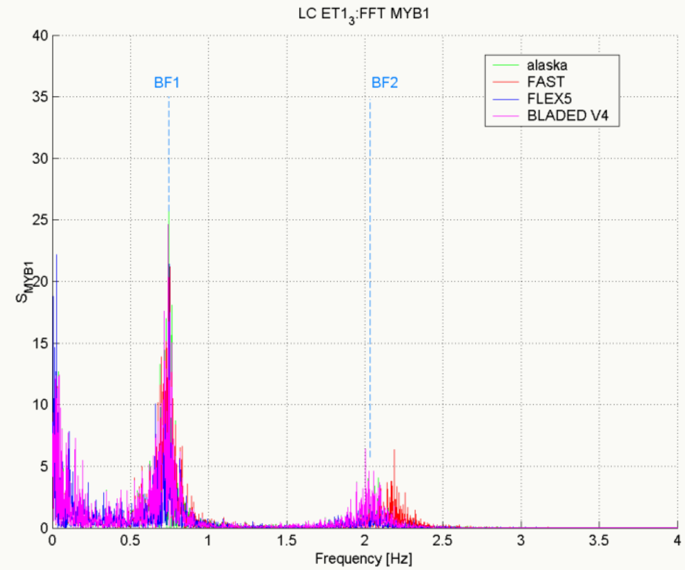



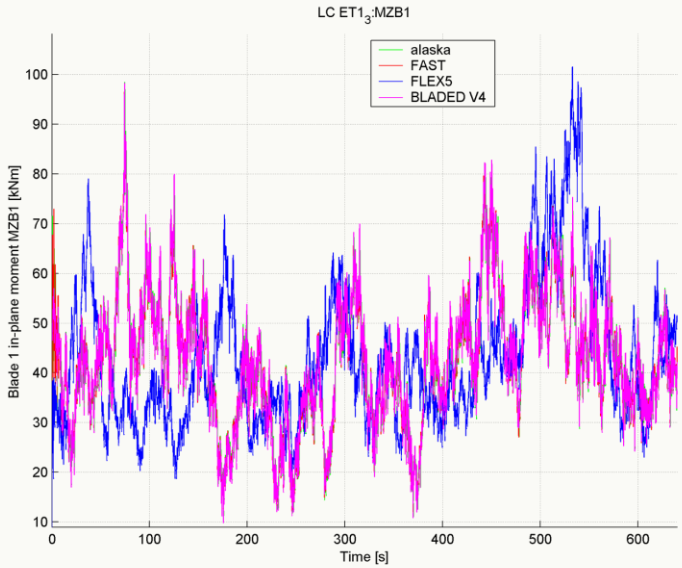
# Load Case LC ET1_3, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

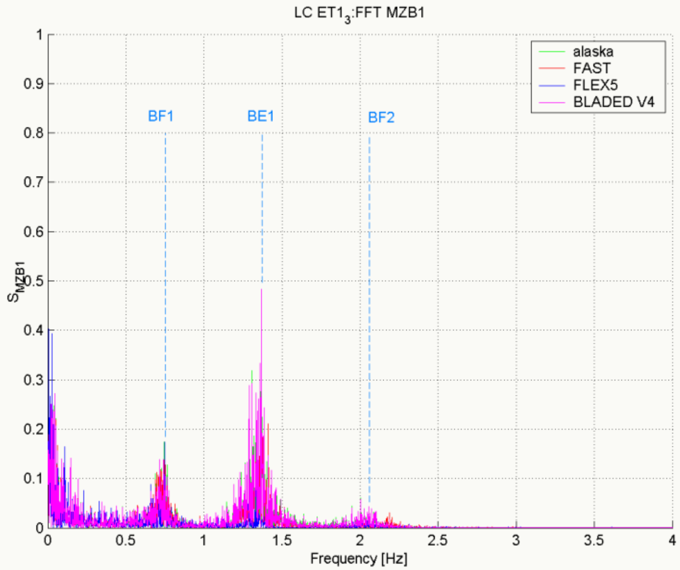


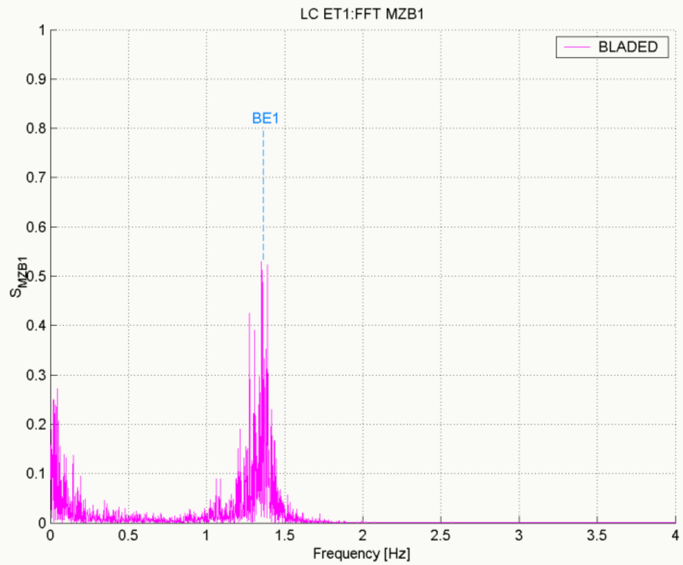



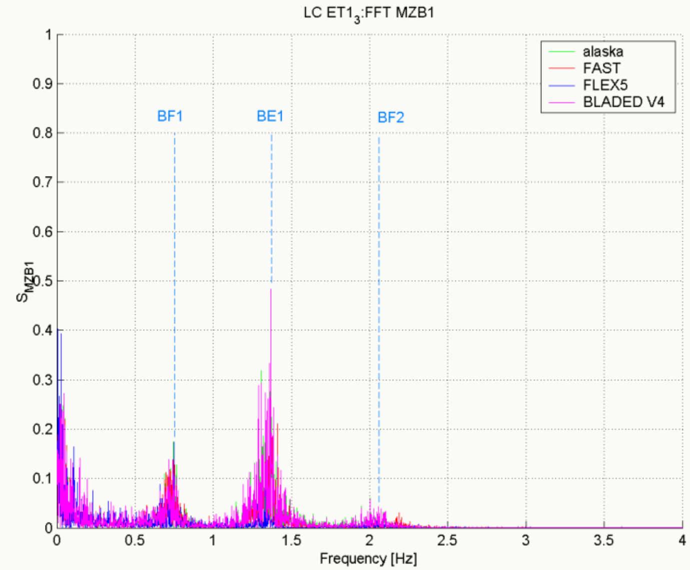



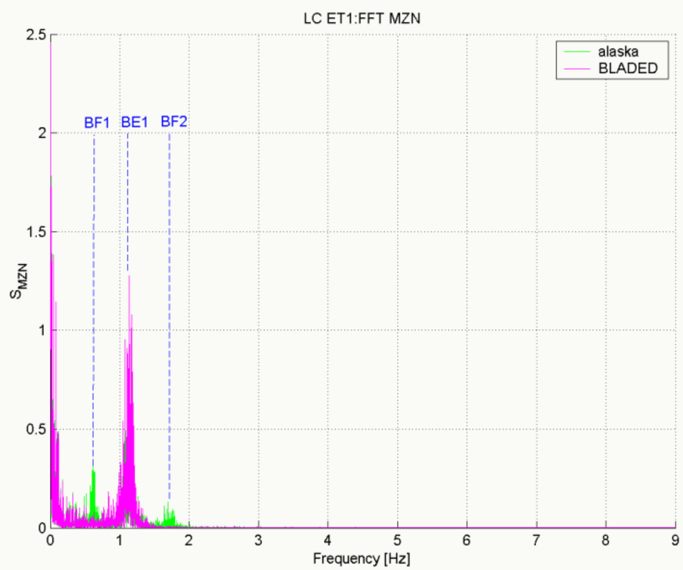

LC ET1_3:MZB1
alaska
FAST
FLEX5
BLADED V4
Blade 1 in-plane moment MZB1 [kNm]
Time [s]

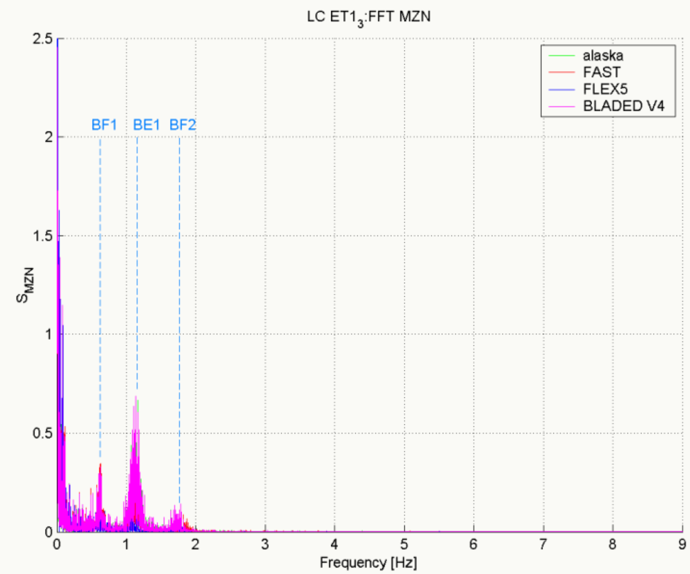

LC ET1_3:FFT MZB1
alaska
FAST
FLEX5
BLADED V4
BF1
BE1
BF2
S_MZB1
Frequency [Hz]



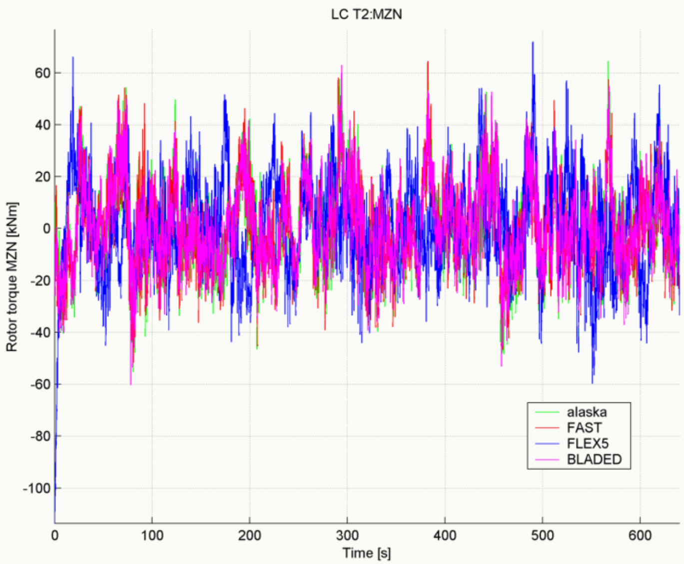



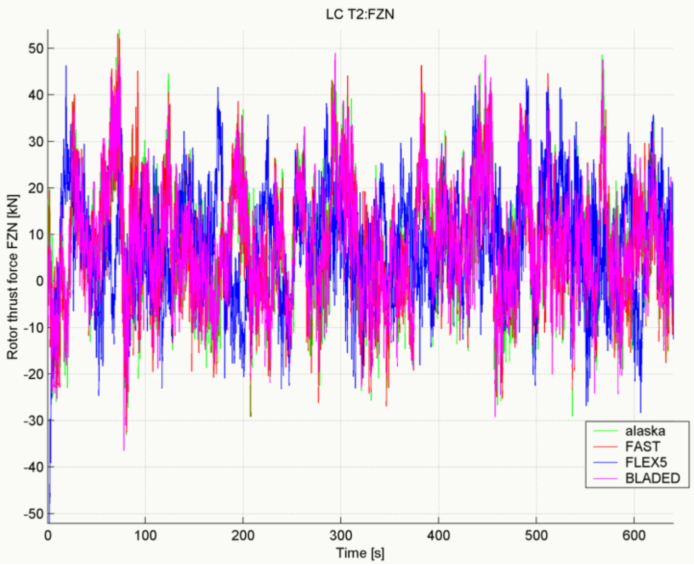

**frequency spectrum of blade 1 in-plane moment for BLADED V3.82 and BLADED V4**



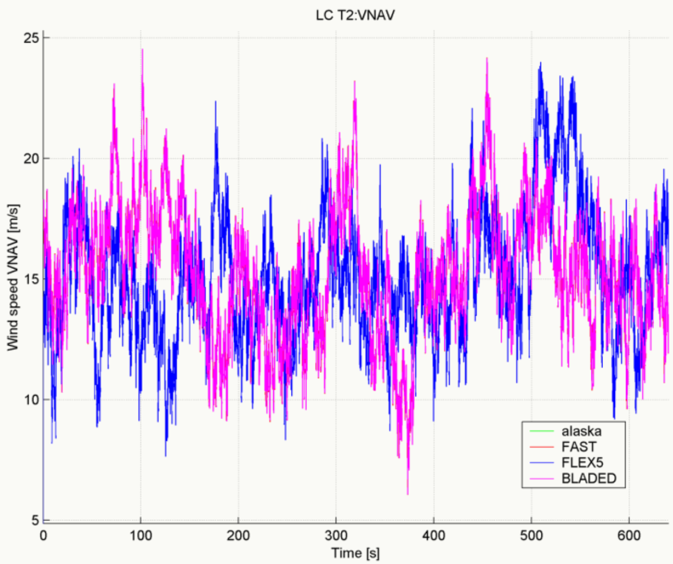




**frequency spectrum of Rotor torque for BLADED V3.82 and BLADED V4**


LC T2:MZN
Rotor torque MZN [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC T2:FZN
Rotor thrust force FZN [kN]
Time [s]
alaska
FAST
FLEX5
BLADED


LC T2:NRot
Rotor speed NRot [rpm]
Time [s]
alaska
FAST
FLEX5
BLADED


LC T2:VNAV
Wind speed VNAV [m/s]
Time [s]
alaska
FAST
FLEX5
BLADED

# Load Case LC T2, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rigid Turbine Model

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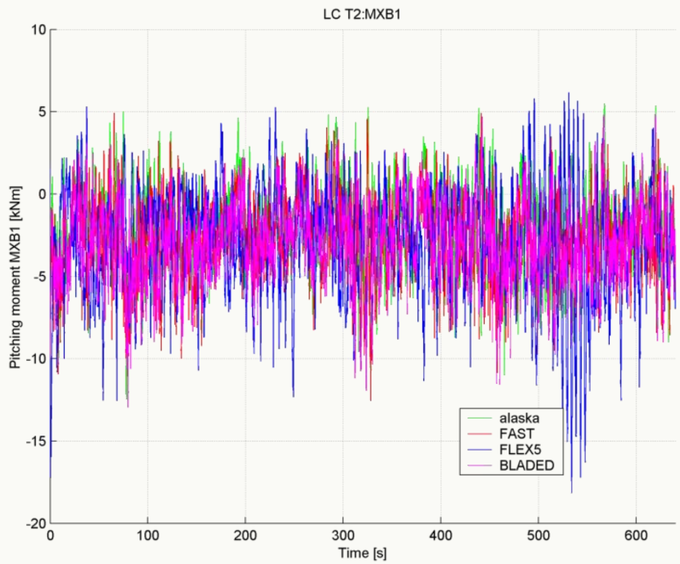
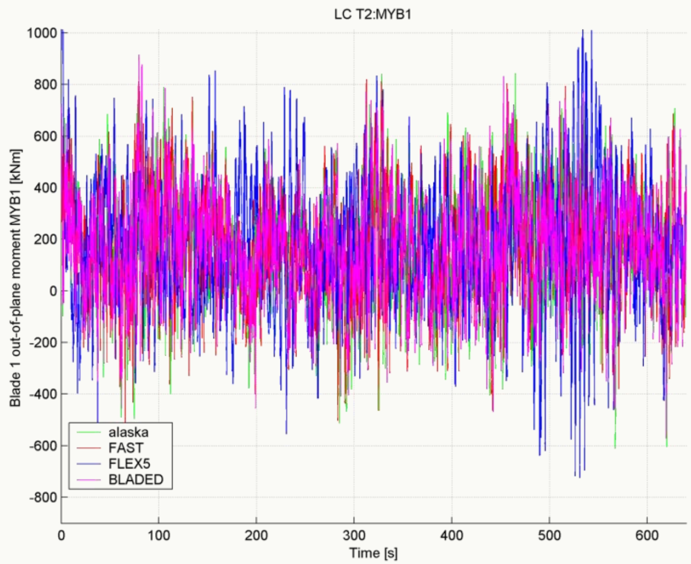
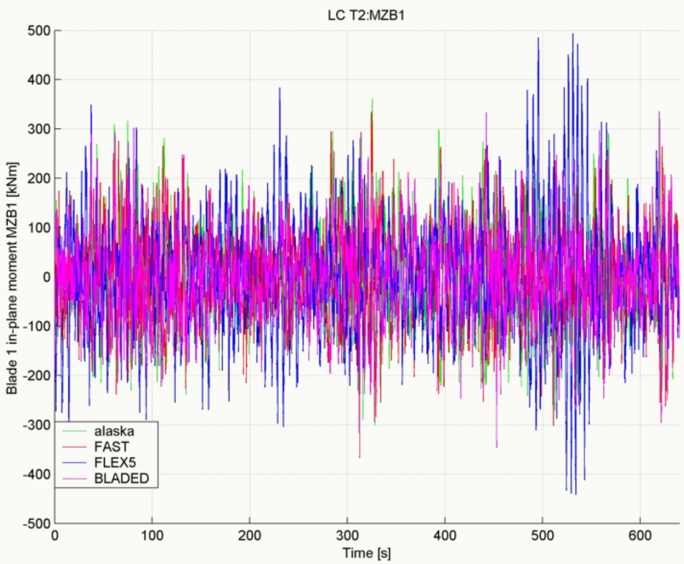
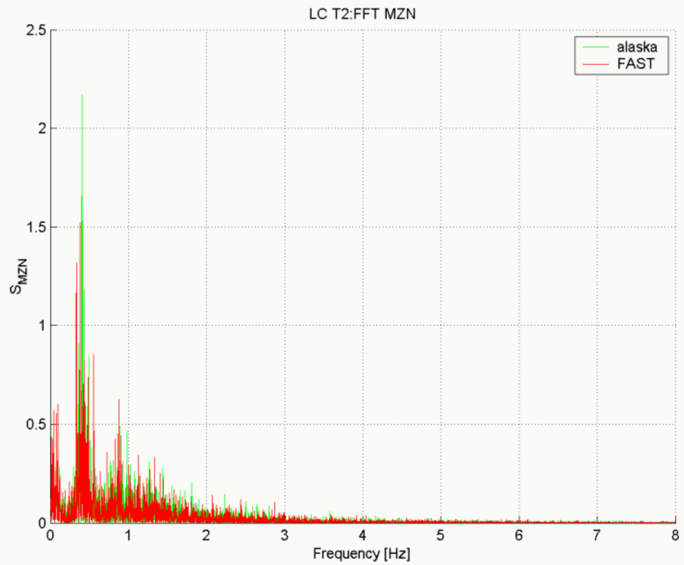


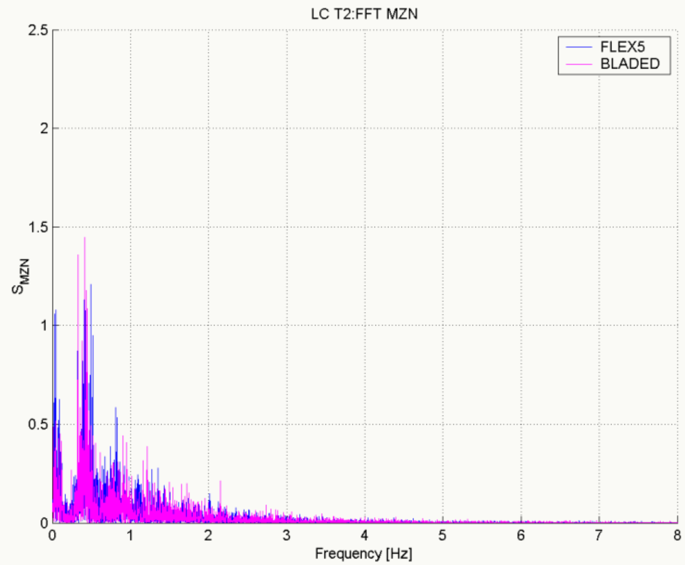



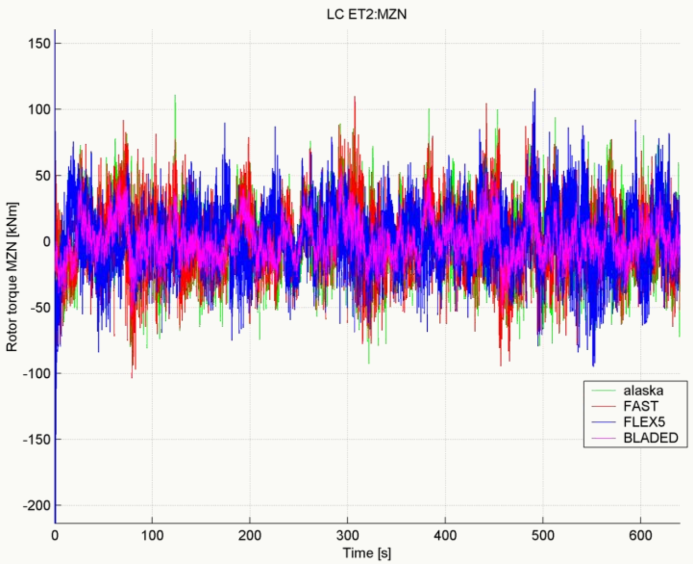



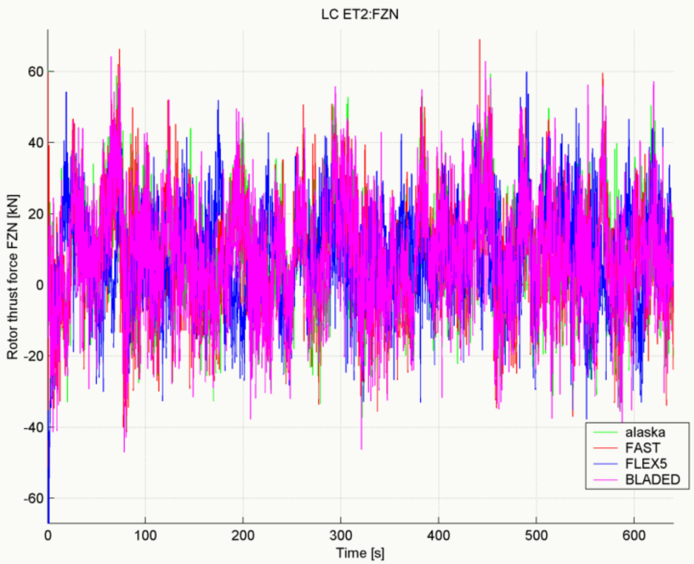
# Load Case LC T2, turb. Wind = 15 m/s, Rotor fixed, Pitch fixed 0°, Yaw fixed 0°, Rigid Turbine Model

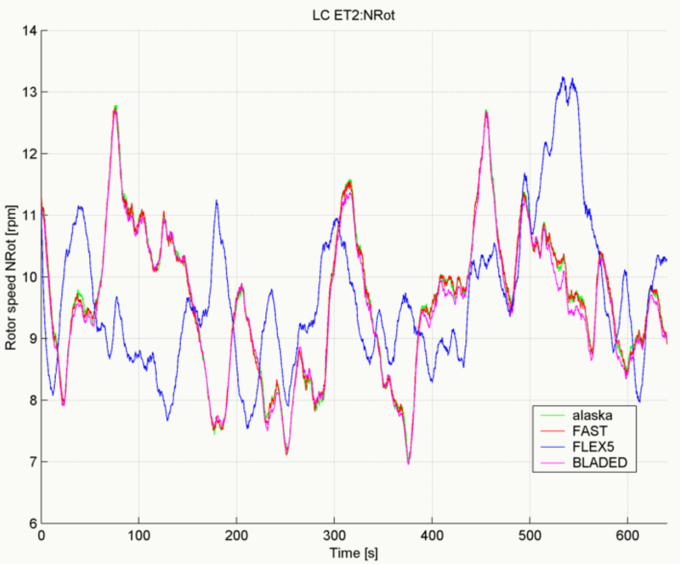


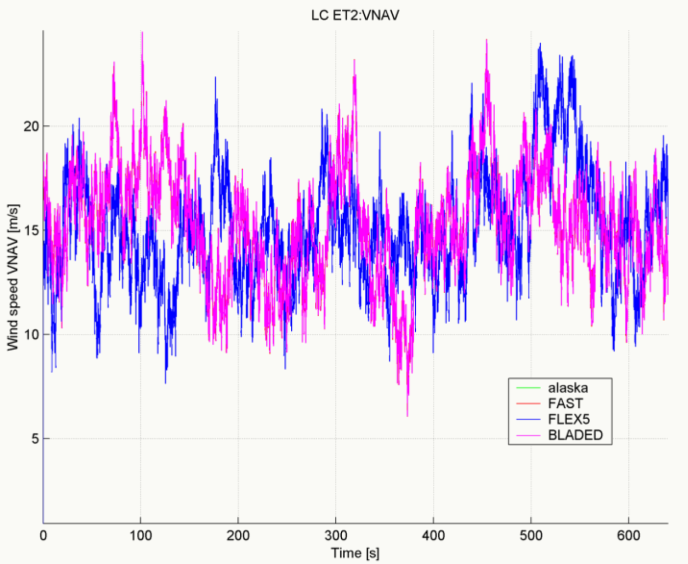



LC ET2:MZN
Rotor torque MZN [kNm]
Time [s]
alaska
FAST
FLEX5
BLADED

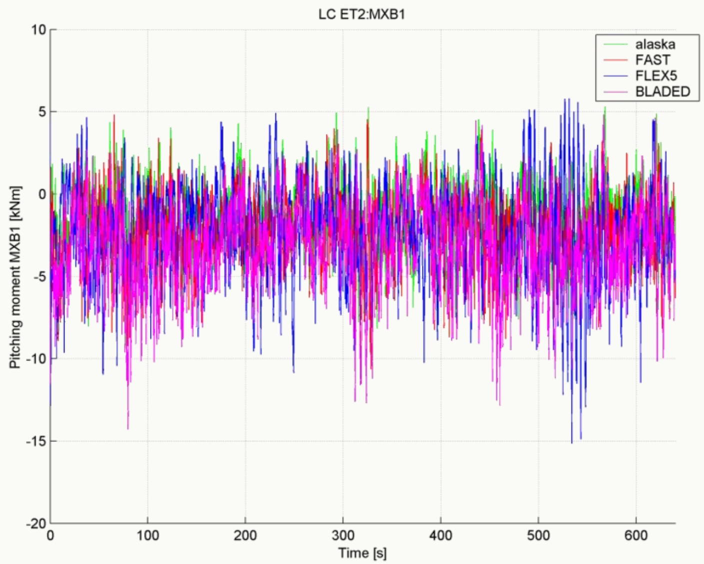

LC ET2:FZN
Rotor thrust force FZN [kN]
Time [s]
alaska
FAST
FLEX5
BLADED

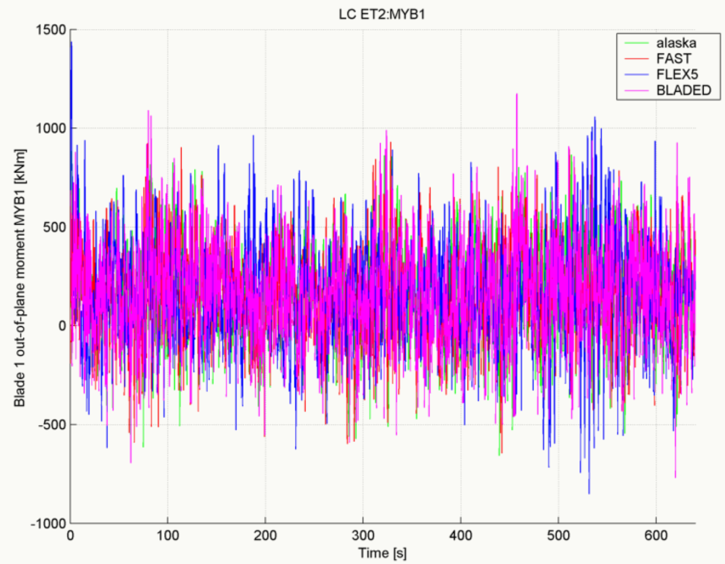

LC ET2:NRot
Rotor speed NRot [rpm]
Time [s]
alaska
FAST
FLEX5
BLADED

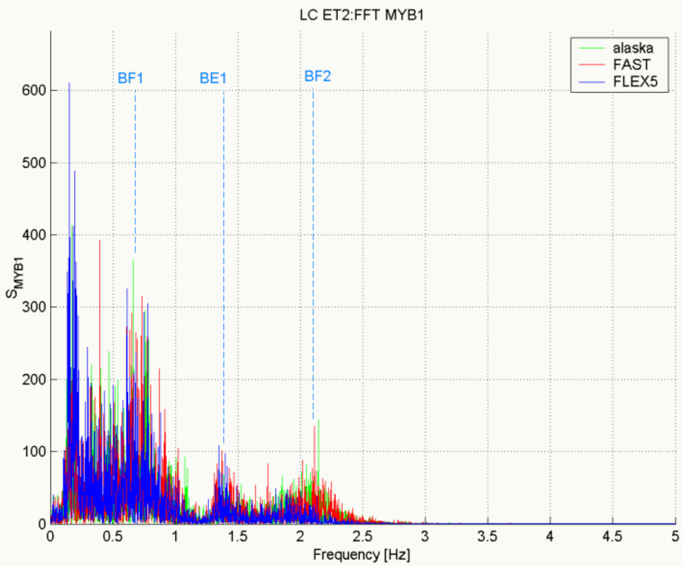

LC ET2:VNAV
Wind speed VNAV [m/s]
Time [s]
alaska
FAST
FLEX5
BLADED

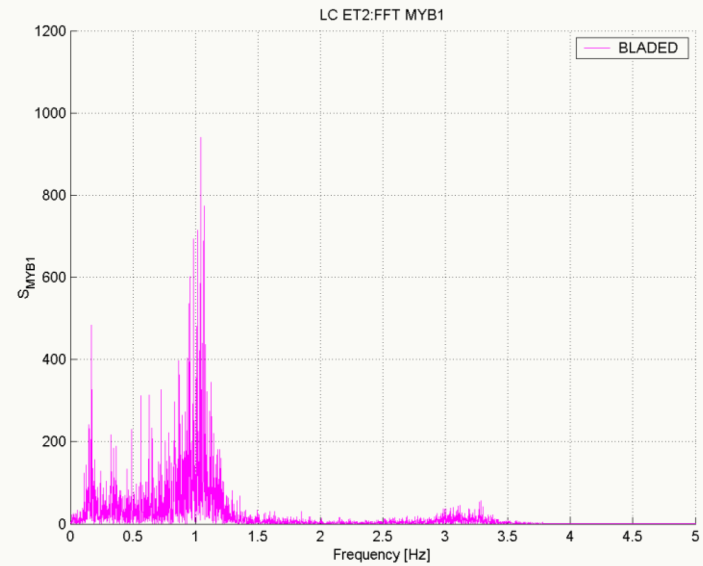
# Load Case LC ET2, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible





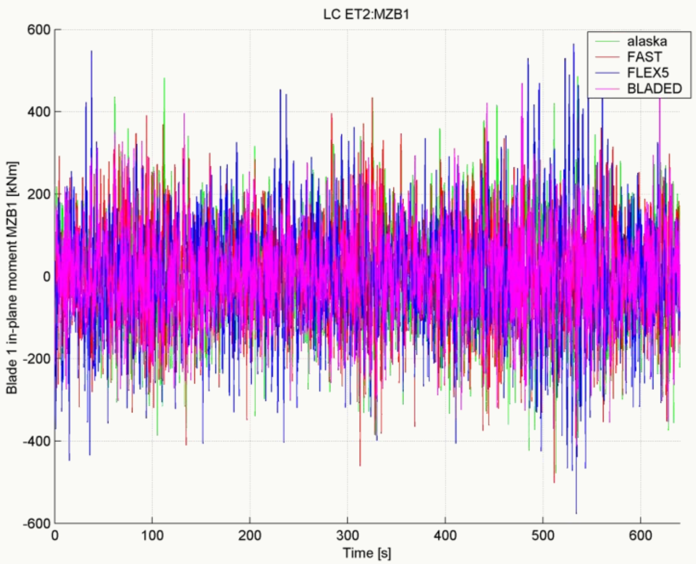



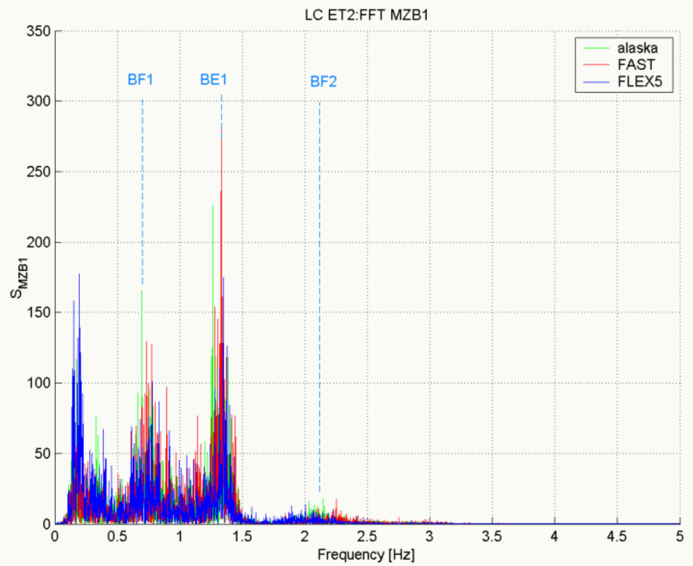



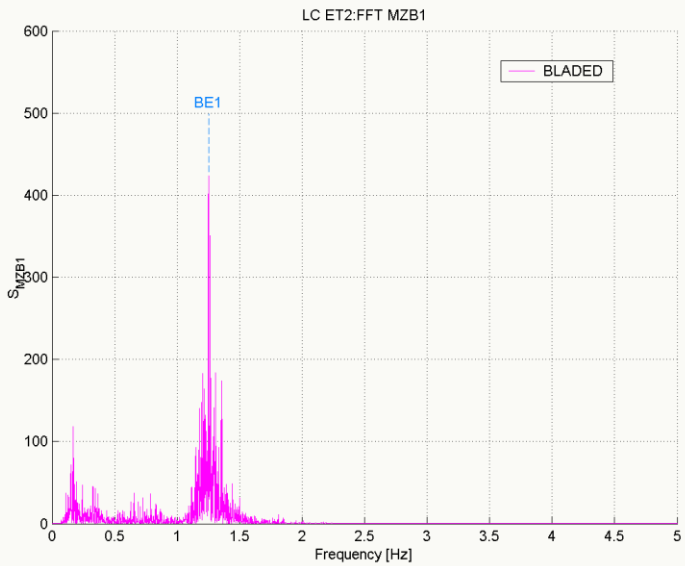



# Load Case LC ET2, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible

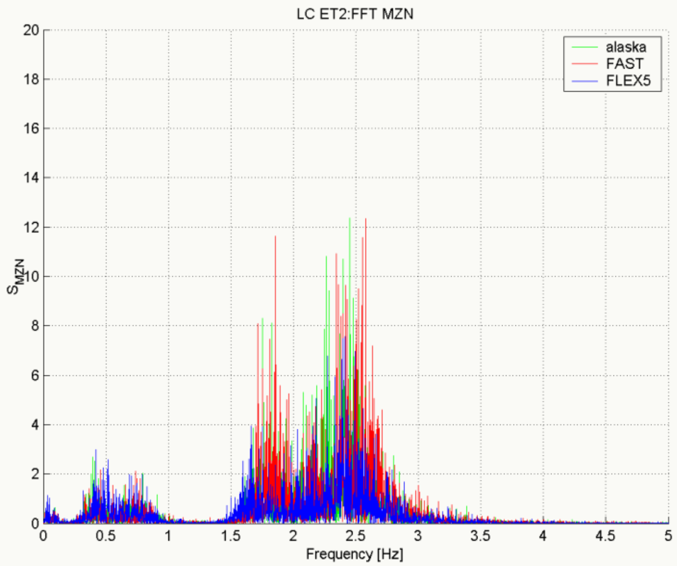


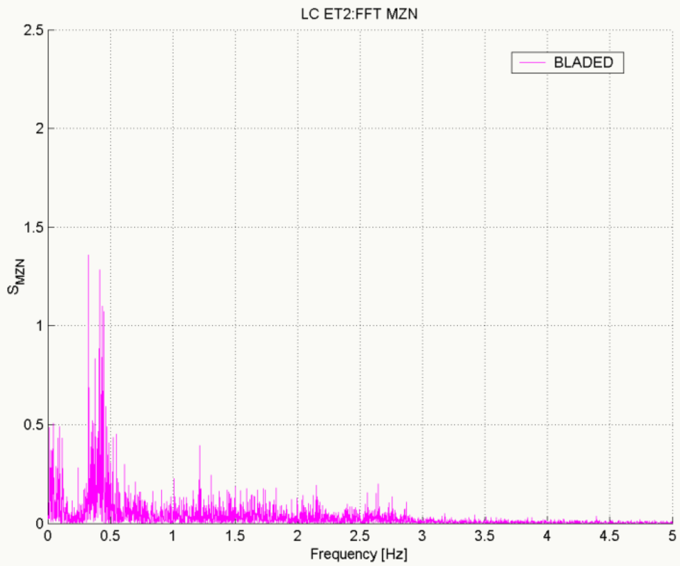


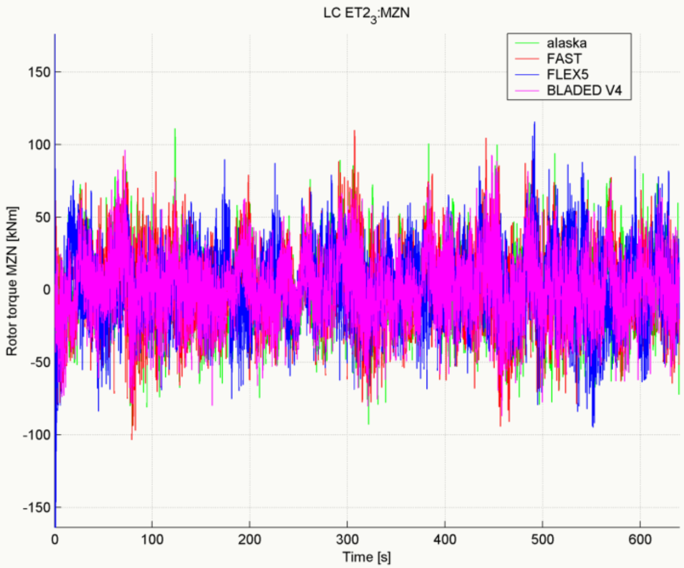
# Load Case LC ET2, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible

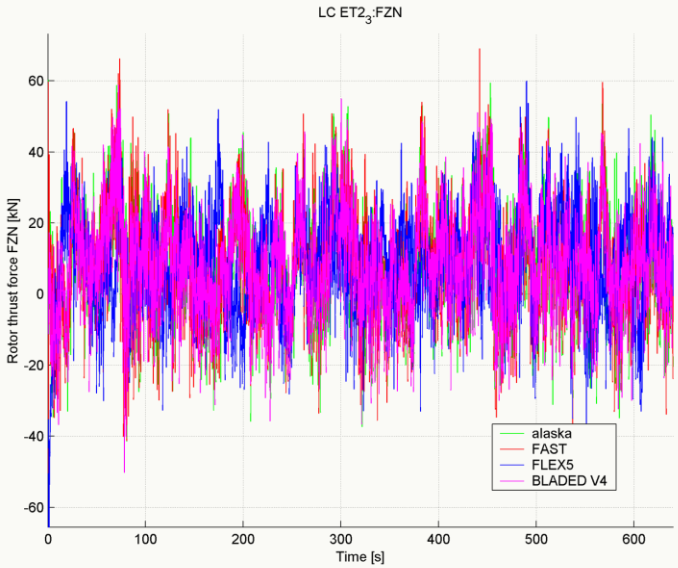


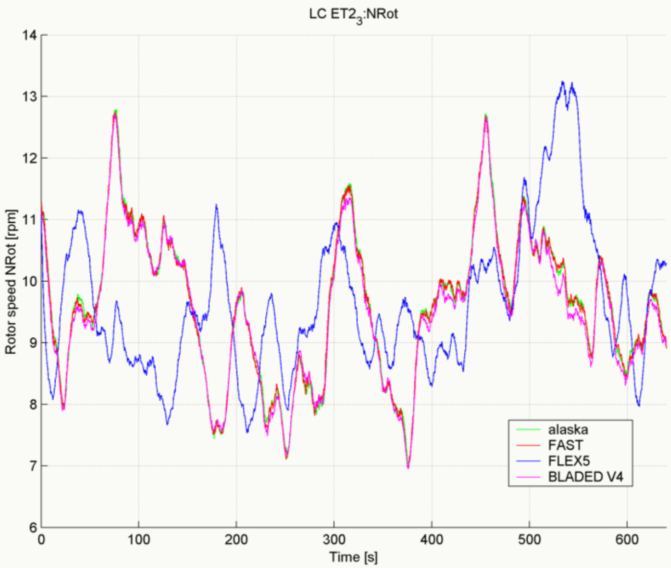



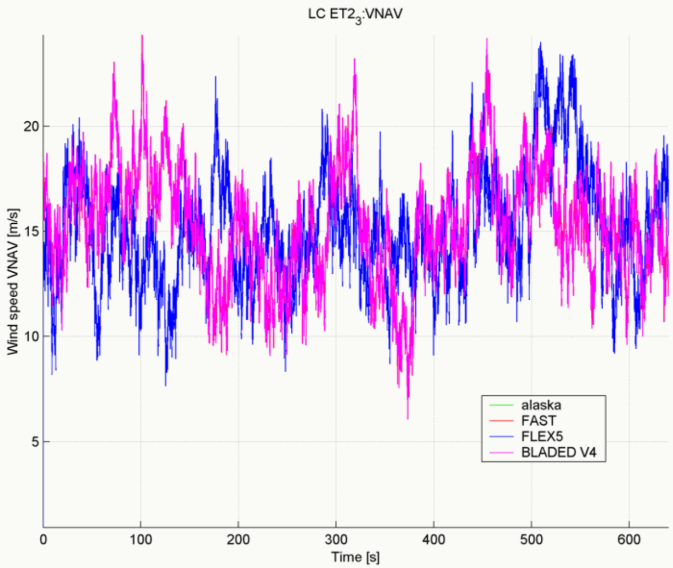
# Load Case LC ET2_3, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

**The load case LC ET2_3 is equivalent to load case LC ET2 except that the new Multibody Dynamics BLADED V4 has been used instead of BLADED V3.82.**


LC ET2_3:MZN
alaska
FAST
FLEX5
BLADED V4
Rotor torque MZN [kNm]
Time [s]


LC ET2_3:FZN
alaska
FAST
FLEX5
BLADED V4
Rotor thrust force FZN [kN]
Time [s]


LC ET2_3:NRot
alaska
FAST
FLEX5
BLADED V4
Rotor speed NRot [rpm]
Time [s]


LC ET2_3:VNAV
alaska
FAST
FLEX5
BLADED V4
Wind speed VNAV [m/s]
Time [s]

# Load Case LC ET2_3, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

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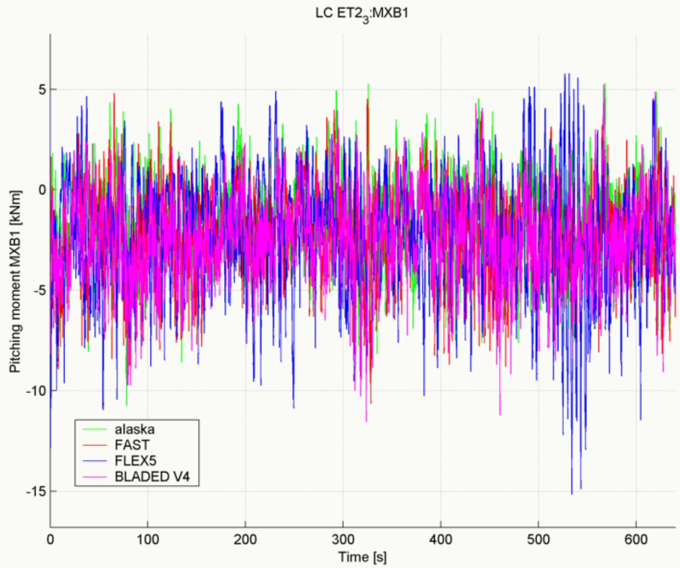
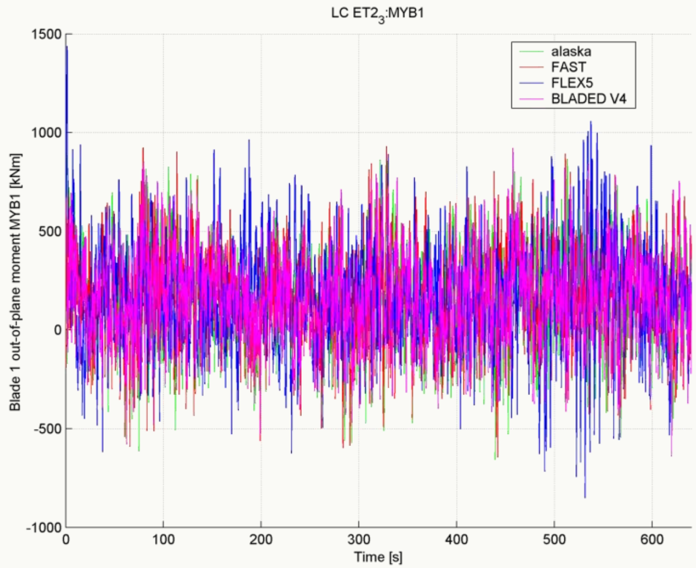
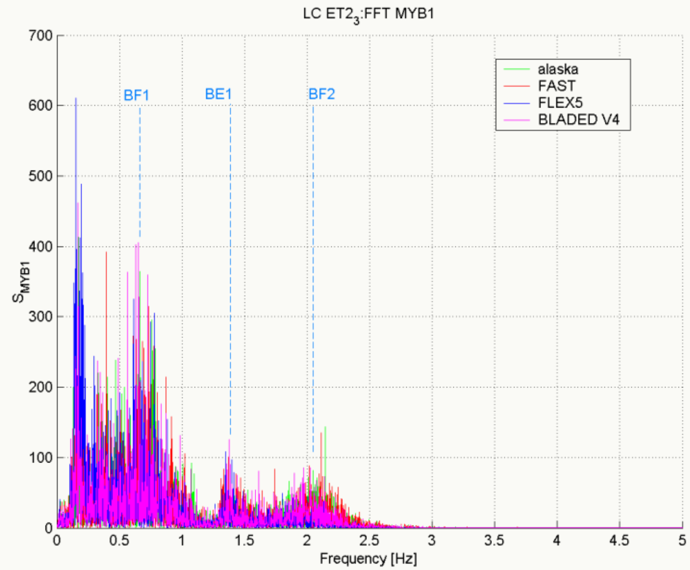
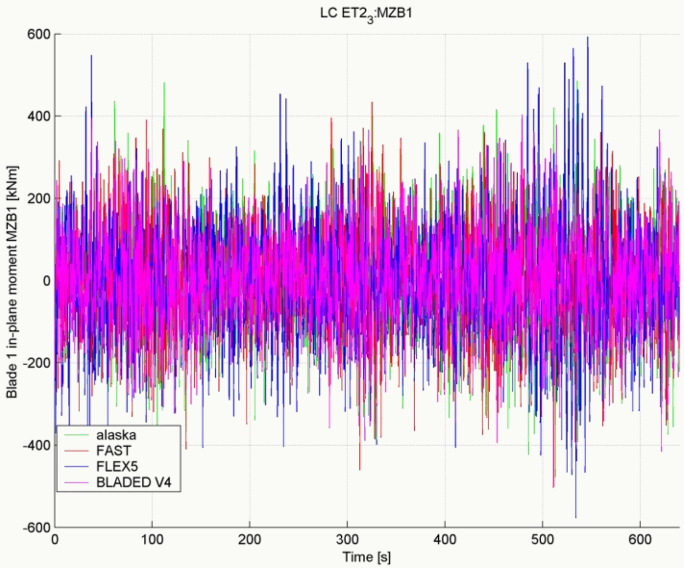


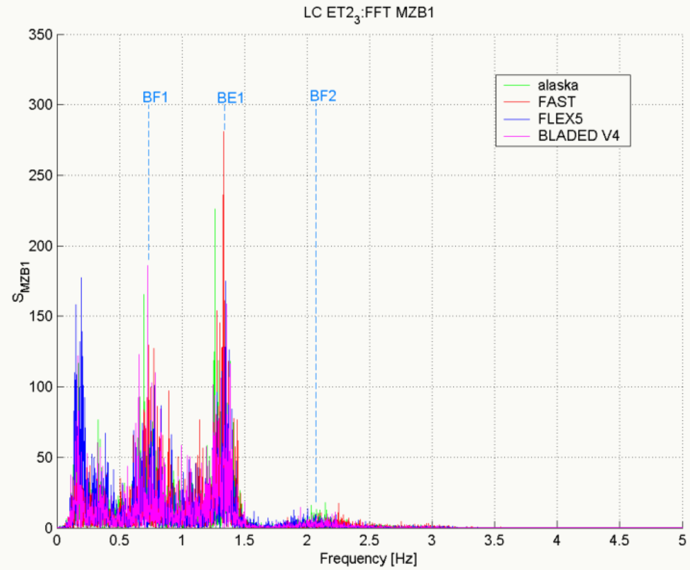



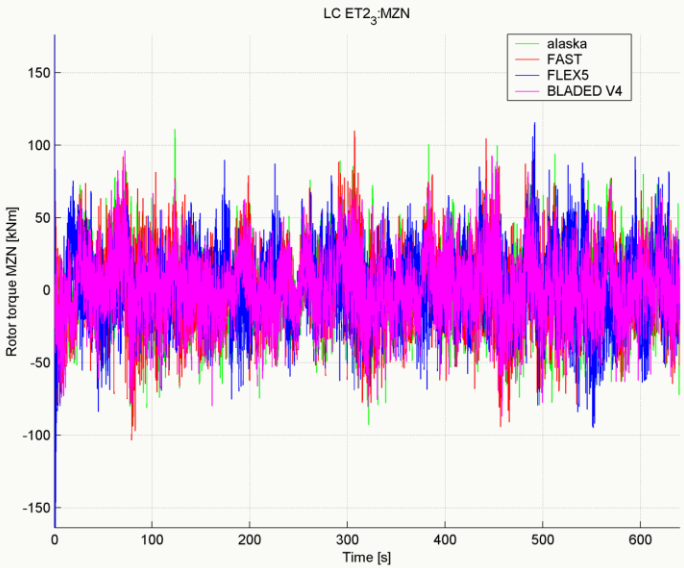



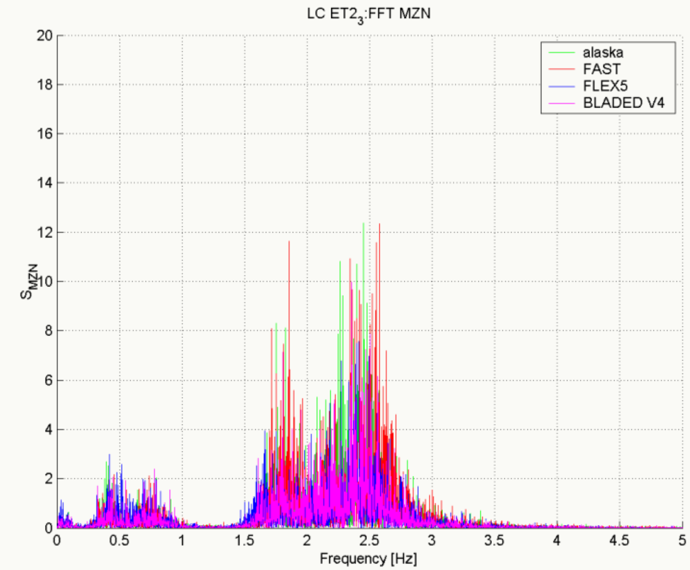
# Load Case LC ET2_3, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4





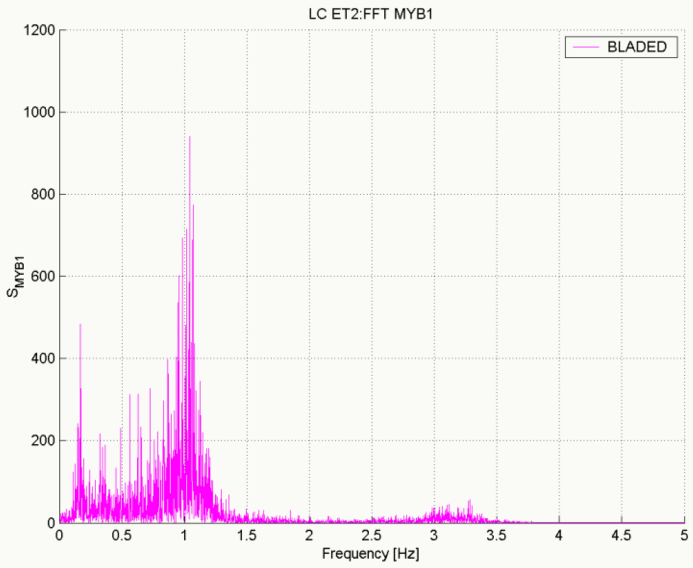



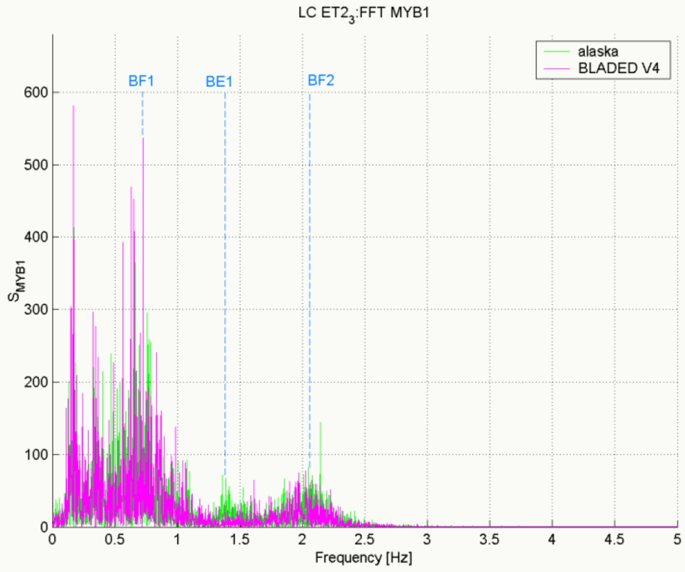



# Load Case LC ET2_3, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4

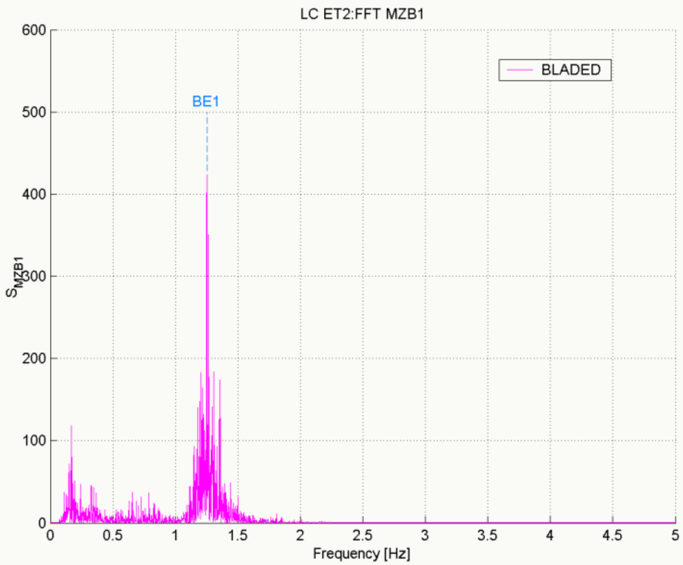


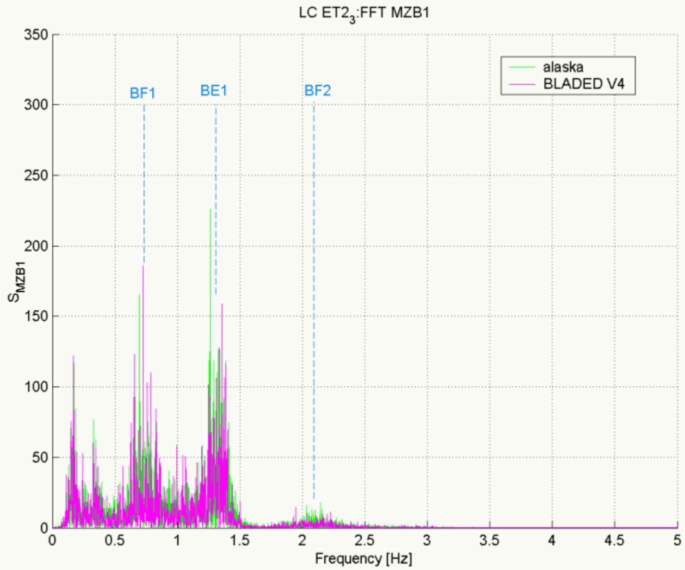


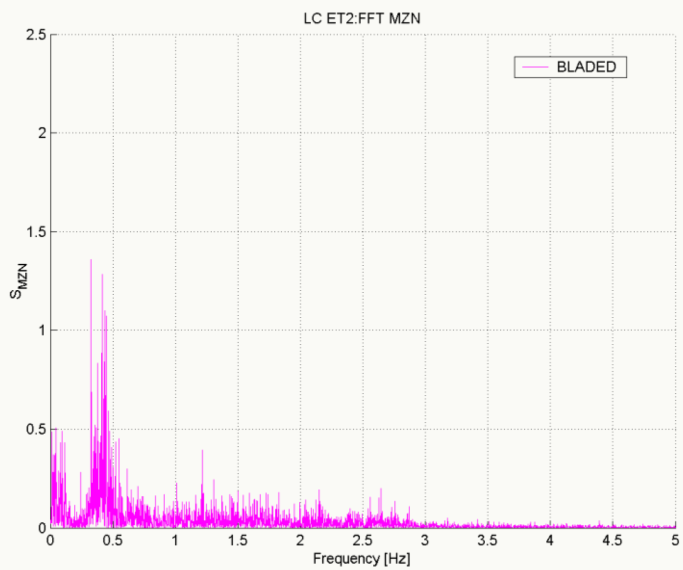

**frequency spectrum of blade 1 out-of-plane moment for BLADED V3.82 and BLADED V4**

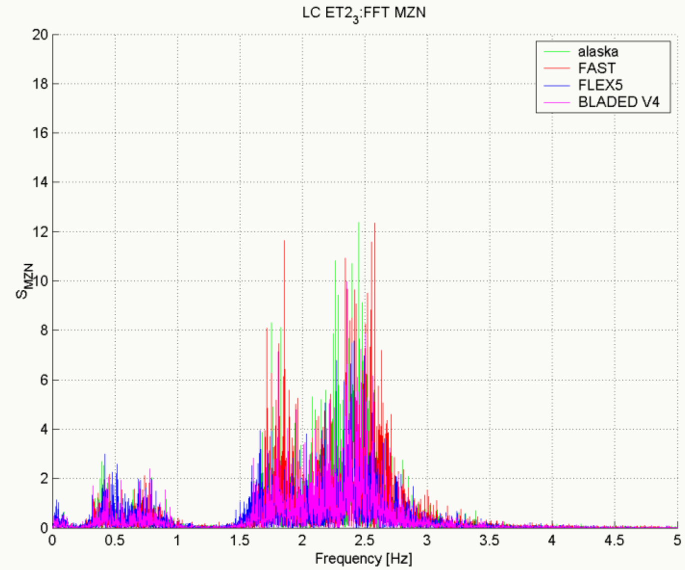
# Load Case LC ET2_3, turb. Wind = 15 m/s, Pitch fixed 30°, Yaw fixed 0°, Rotor Blades flexible, BLADED V4




**frequency spectrum of blade 1 in-plane moment for BLADED V3.82 and BLADED V4**




**frequency spectrum of Rotor torque for BLADED V3.82 and BLADED V4**

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## LCGroup IV

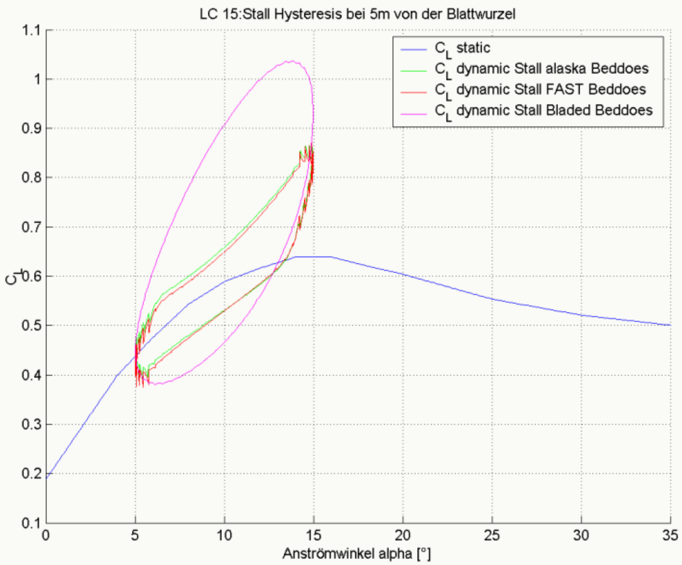
| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Pitch | Yaw | Rotor IC | Generator / Motor | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | Eql/GDW | None/Bed/Oye | on/off | on/off | None/Log/Exp | [s] | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | on/off | const/var [m/s] | const/var | [on/off] | [s] | [s] |
| 15 | Eql | Bed | on | off | None | 0.02 | off | off | fixed, 90° | fixed, 0° | 0 | off | 60 | var1 | off | 0,001 | 6 |
| 15_1 | Eql | Oye | on | off | None | 0.02 | off | off | fixed, 90° | fixed, 0° | 0 | off | 60 | var1 | off | 0,001 | 6 |
| 16 | Eql | Bed | on | off | None | 0.02 | off | off | fixed, 90° | fixed, 0° | 0 | off | 60 | var2 | off | 0,001 | 6 |
| 16_1 | Eql | Oye | on | off | None | 0.02 | off | off | fixed, 90° | fixed, 0° | 0 | off | 60 | var2 | off | 0,001 | 6 |

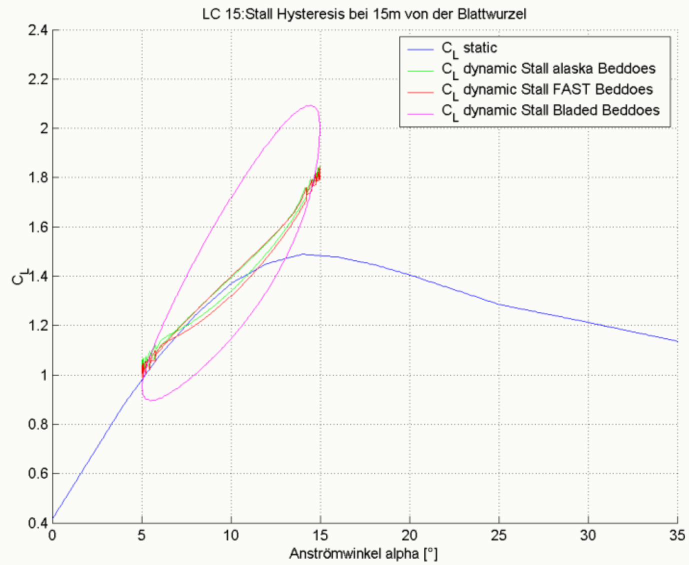
- **Rotor fixed**
- **Rigid rotor blades without twist and pre-bent**
- **Pitch fixed 90°**
- **Cyclic variations of the angle of attack with 2 Hz by a change in wind yaw**

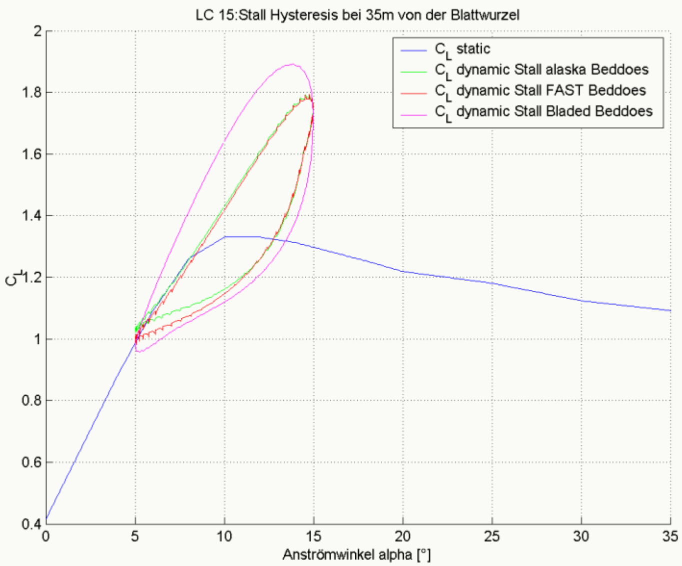
**Dynamic stall is a non-linear, unsteady aerodynamic effect that occurs when the angle of attack of the airfoils change rapidly. This will subsequently affect the lift of the airfoils. In load case group LCGroup IV different dynamic stall models has been validated. alaska/Wind, BLADED, and FAST support a Beddoes-Leishmann [4] stall model where the Stig Øye [5] stall model is available in alaska/Wind and FLEX5.**

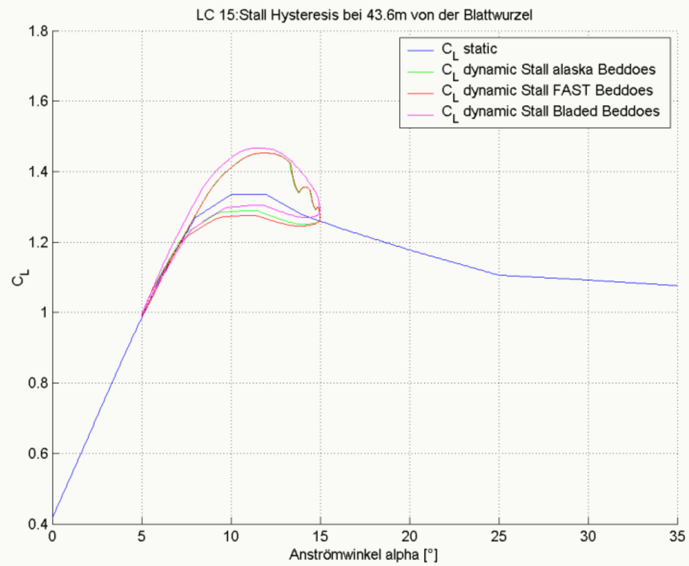
# Load Case LC 15, const. Wind = 60 m/s, Rotor fixed, Pitch fixed 90°, Yaw fixed 0°, wind yaw cyclic variations 2Hz





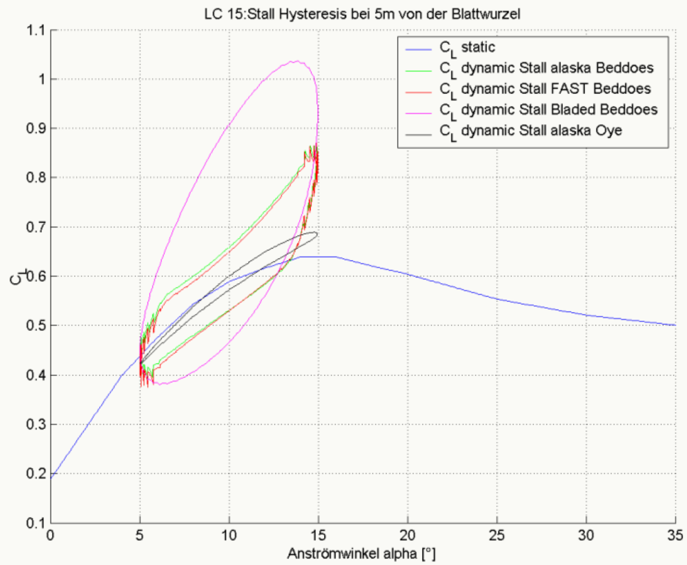



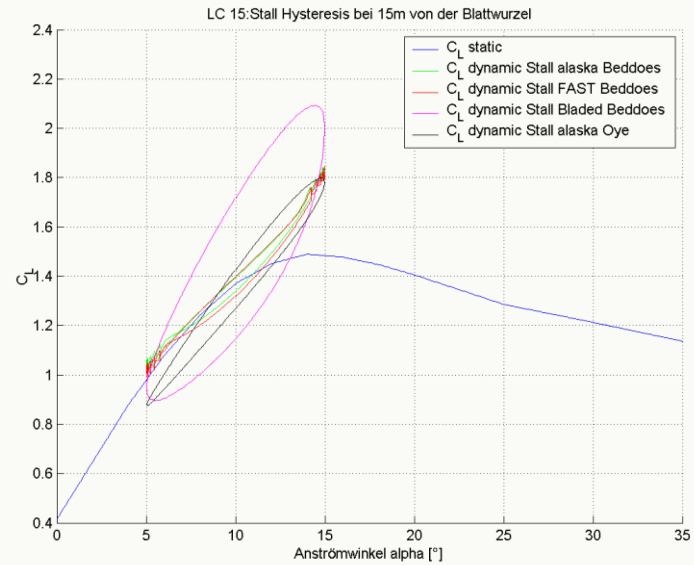



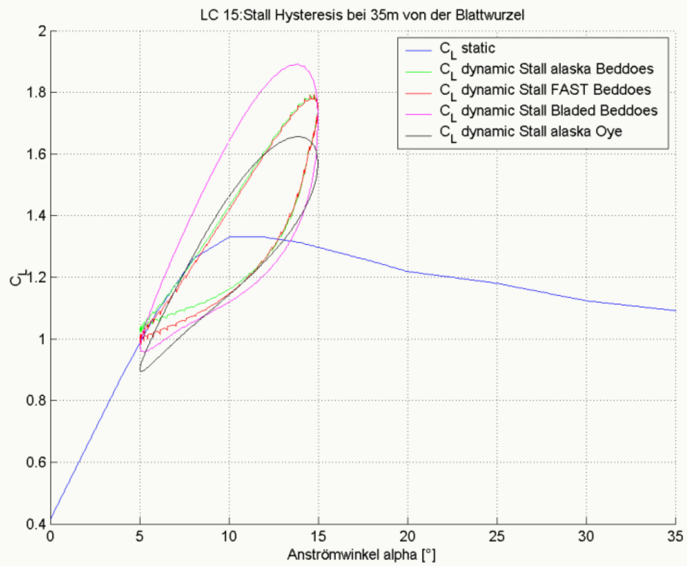



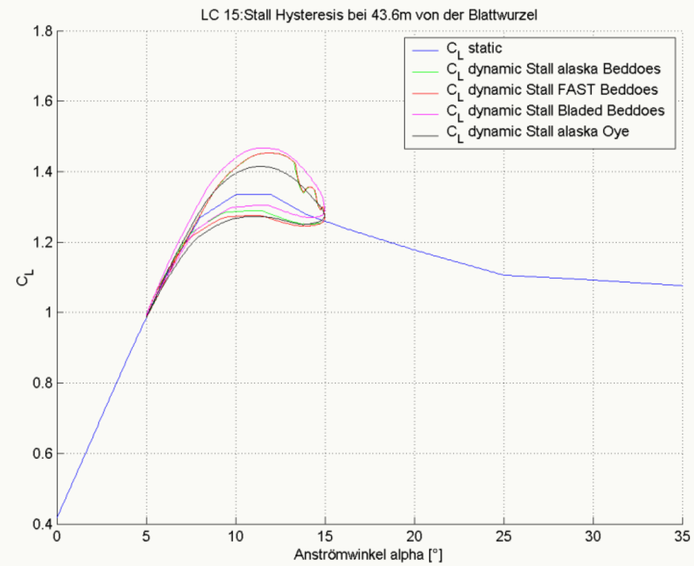
# Load Case LC 15_1, equivalent to load case LC 15 including Stig Øye stall model





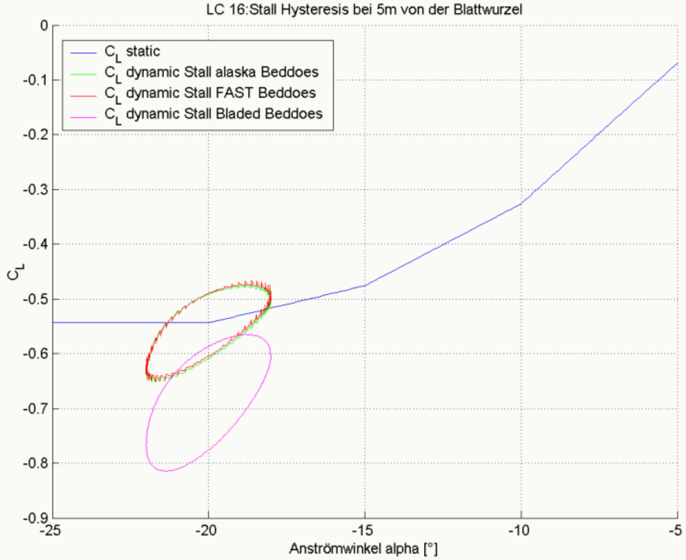



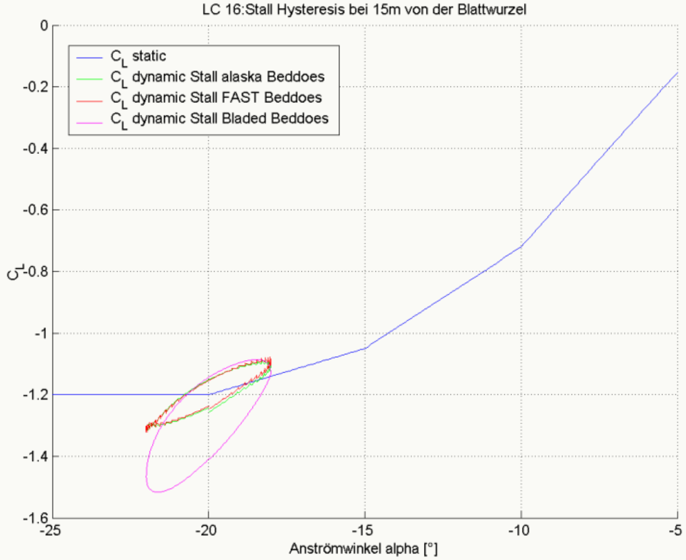



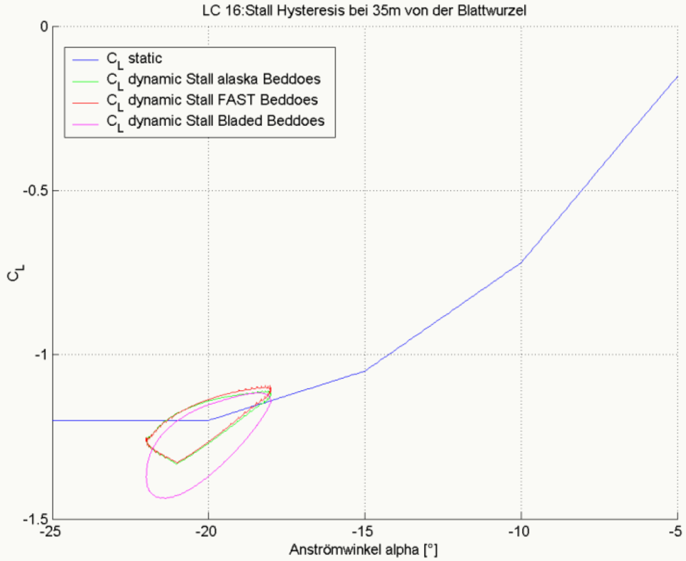



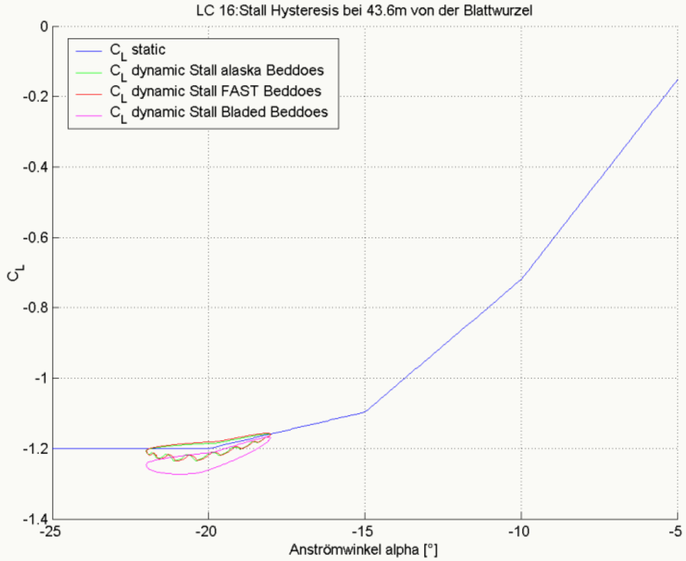
# Load Case LC 16, const. Wind = 60 m/s, Rotor fixed, Pitch fixed 90°, Yaw fixed 0°, wind yaw cyclic variations 2Hz



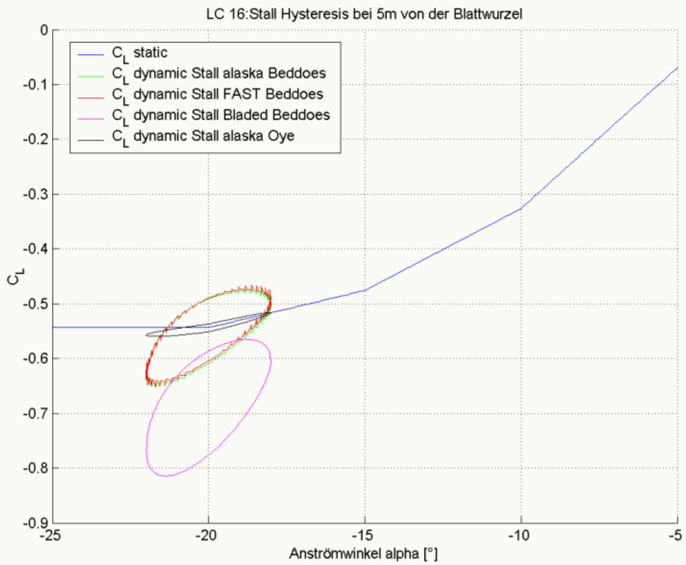


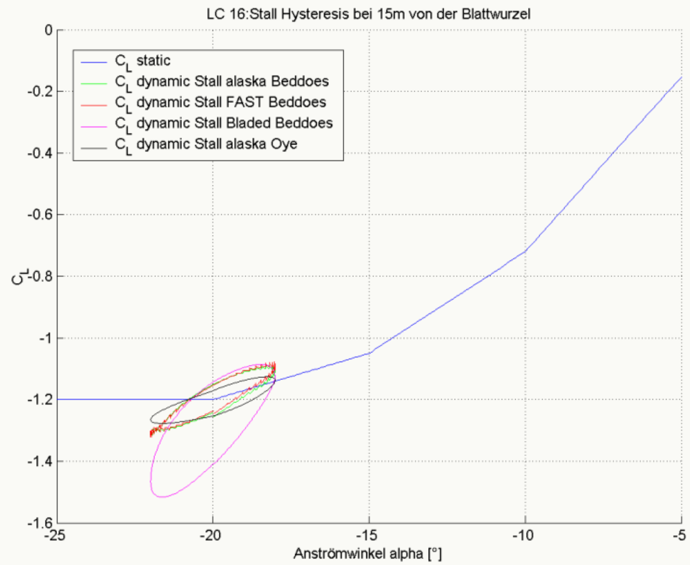



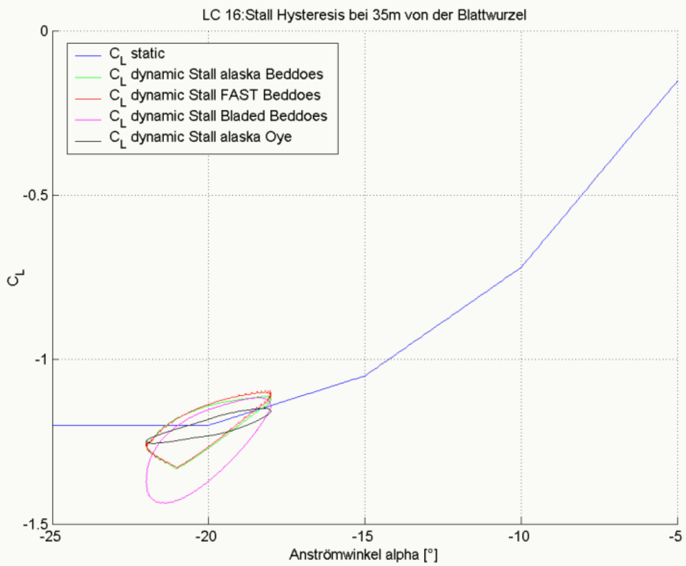



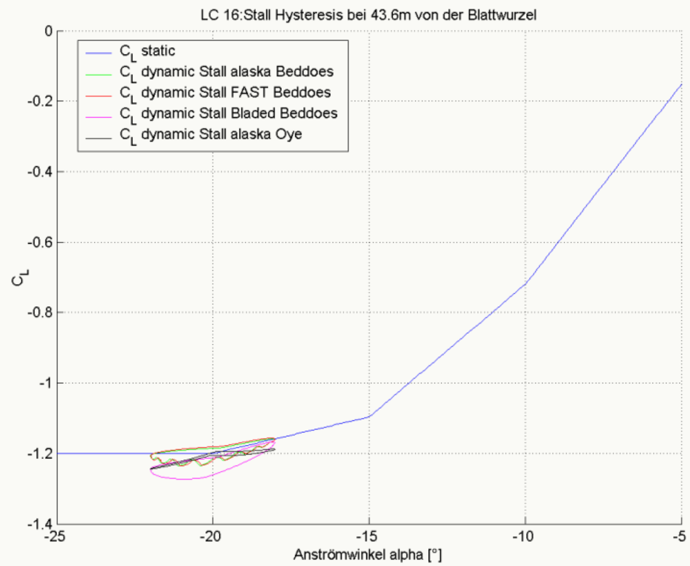



# Load Case LC 16_1, equivalent to load case LC 16 including Stig Øye stall model



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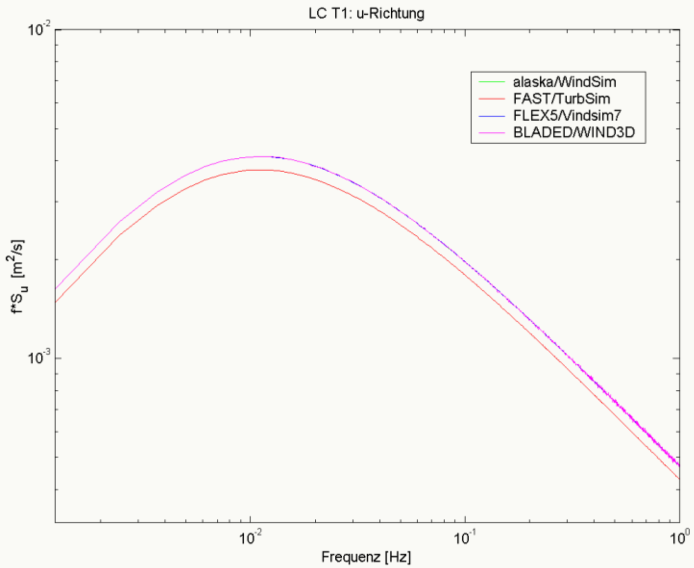
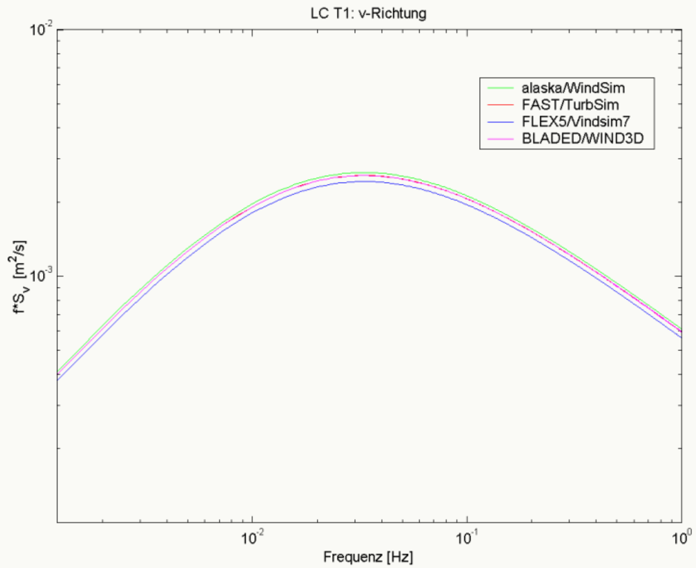
## LCGroup I_TurbSim
## Comparison of Synthetic Turbulent Wind Fields

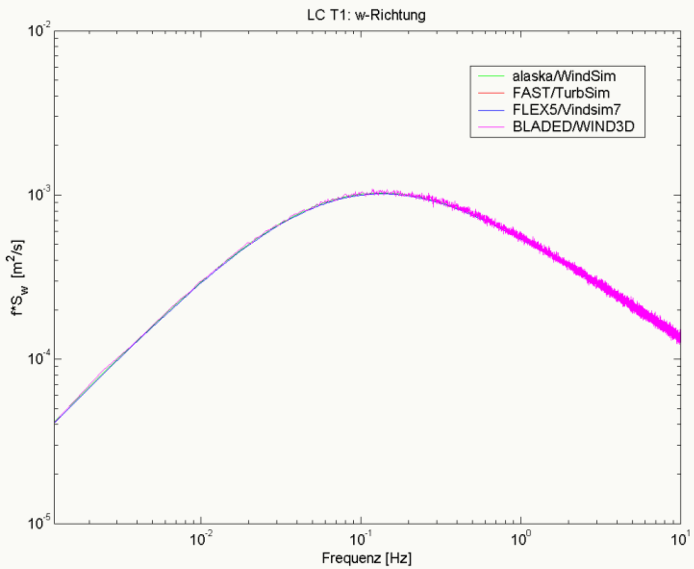
| LC Id | Aerodynamics | | | | | | | | | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Turbulence Model | Mean Wind Speed | Turbulence Intensity | Wind Shear | Grid Width | Grid Height | Reference Height | Hub Height | Grid Points vertical | Grid Points horizontal | Turbulence Seed | Time Step | $T_{total}$ |
| | | [m/s] | [%] | [on/off] | [m] | [m] | [m] | [m] | | | | [s] | [s] |
| T1 | Kaimal | 15 | 18 | off | 100 | 100 | 78.55 | 78.55 | 9 | 9 | 13 | 0,05 | 819.2 |

**For the simulation with turbulent wind, a full-field turbulent wind description is necessary. This can be get by measured data or a wind field simulator. In load case LC T1, a comparison of the results of different wind field simulators based on the same IEC Kaimal spectral model has been carried out.**

# Load Case LC T1, IEC Kaimal spectral model



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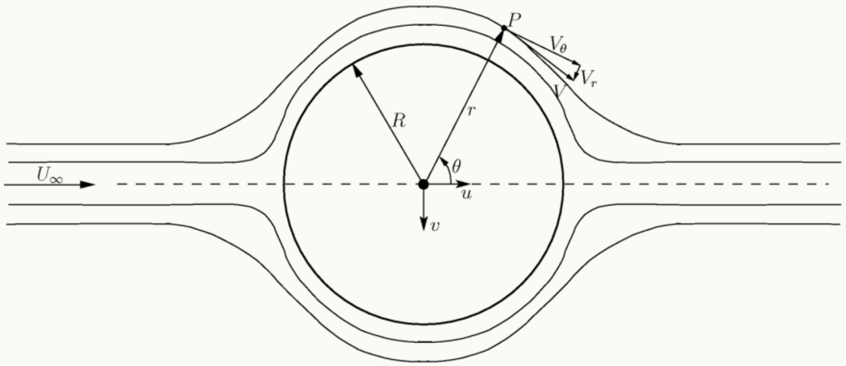
## LCGroup I_TS
## Comparison of tower shadow models

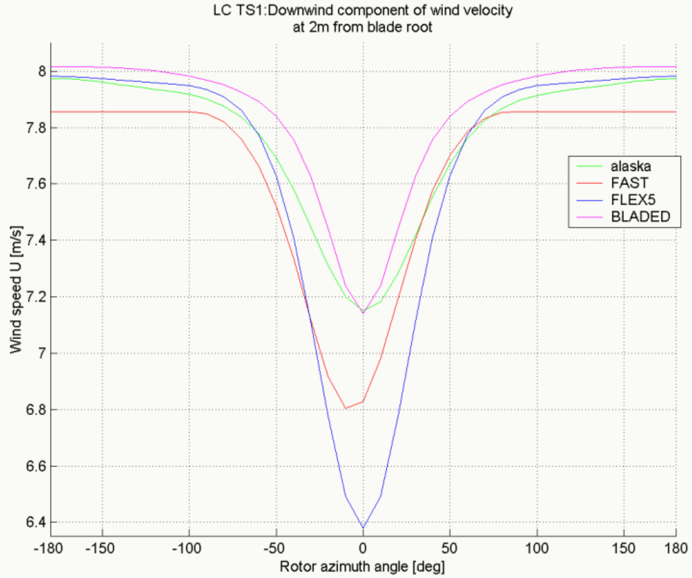
| LC Id | Aerodynamics | | | | | | Turbine Model | | | | | | | Wind | | | Simulation Control | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wake Modell | Dynamic Stall | Tip Loss Model | Tower Shadow | Wind Shear Model | Eval Time Step | Gravity | Rotor DOF | Pitch | Yaw | Rotor IC | Rotor Azimuth | Generator / Motor | $v_{Hub}$ | YawErr | Turbulence | Time Step | $T_{total}$ |
| | Eql/GDW | None/ Bed/Oye | on/off | on/off | None/ Log/Exp | [s] | on/off | on/off | controlled/ fixed | controlled/ fixed | [rpm] | | on/off | const/var [m/s] | const/var | [on/off] | [s] | [s] |
| TS1 | Eql | None | on | on | None | 0.02 | off | off | fixed, 0° | fixed, 0° | 0 | 0° - 360° | off | 8 | 0° | off | 0,02 | 2 |

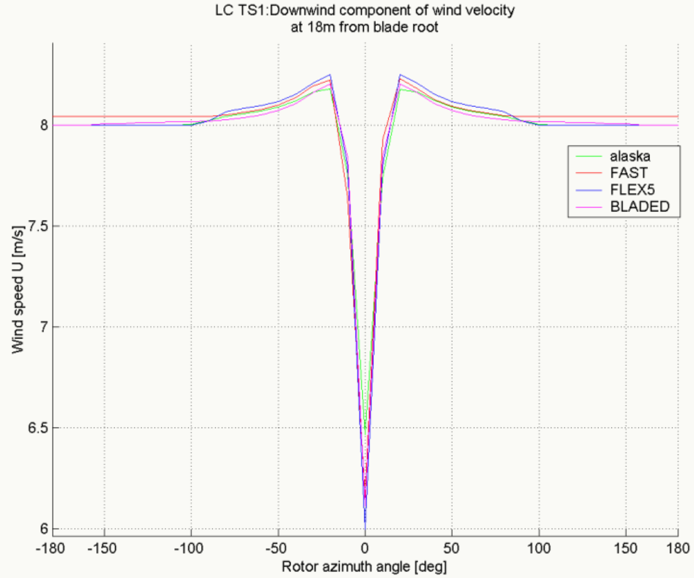
**The wind turbine tower influences the local velocity field around the tower. In front of the tower, the wind speed will decrease and increase along the sides. This effect can be considered by the use of tower influence models. They are usually based on a potential flow method around a circular cylinder. In load case LC TS1, the different tower influence models have been compared. For selected blade stations, the wind speed has been recorded during the variation of the rotor azimuth angle.**

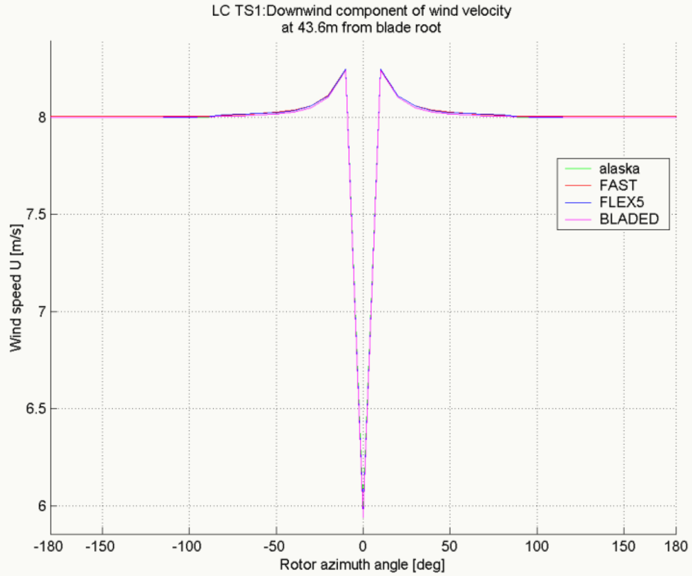


# Load Case LC TS1, const. Wind = 8 m/s, variation of rotor azimuth angle, Pitch fixed 0°, Yaw fixed 0°





# CPU Time Comparison



**To be able to make a quantitative classification of load case simulation, a CPU time comparison for selected load cases has been carried out. The different runs have been done by a HP workstation with a 2 GHz dual-core processor and an 8 GB RAM. In alaska, FAST, and FLEX5 the simulation has been carried out in a batch mode without a graphical user interface. Currently, BLADED does not support a mode without a graphical user interface. The recorded CPU time for BLADED is therefore not very meaningful, and is given only for completeness!**

| LC Id | Total simulation time [s] | CPU - TIME [s] | | | |
|---|---|---|---|---|---|
| | | alaska | BLADED 3.82 / 4 | FAST | FLEX5 |
| 5 | 300 | 30,4 | 104 / 156 | 13,7 | 13,9 |
| ET1 | 640 | 84,9 | 170 / 216 | 33,6 | 30,5 |
| ET2 | 640 | 106 | 223 / 387 | 33,8 | 31,3 |
| T2 | 640 | 62,2 | 224 / 331 | 31,2 | 30,5 |

# References

[1] Wind Turbine Design Codes: A Validation of alaska/Wind in comparison with BLADED, FAST, and FLEX5, Online:
URL: http://www.ifm-chemnitz.de/produkte-html/alaWind_Downloads.html [2011-29-04]

[2] NWTC Design Codes (TurbSim by Neil Kelley, Bonnie Jonkman), Online:
URL: http://wind.nrel.gov/designcodes/preprocessors/turbsim/ [2011-03-02]

[3] Hansen, M.O.L.: Aerodynamics of Wind Turbines Application (Second Edition), Earthscan in the UK, London 2008

[4] Beddoes, T.S., Leishmann, J.G.: A Semi-Empirical Model for Dynamic Stall, Journal of the American Helicopter Society, July 1989

[5] Øye, S.: Dynamic stall, simulated as time lag of separation by Stig Øye, Department of Fluid Mechanics Technical University of Denmark