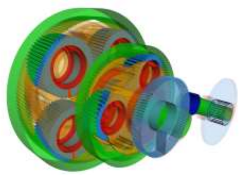

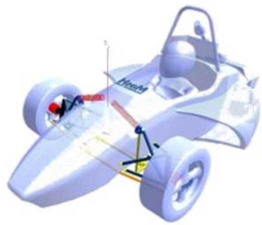

DEVELOPING AN AEROELASTIC STABILITY ANALYSIS PROCESS FOR LARGE WIND TURBINES USING MULTIBODY SIMULATION

SIMULIA Multibody Simulation User Group Meeting 2016

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- Developed Stability Analysis Tool
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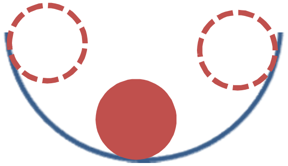
- Conclusions and Current Work

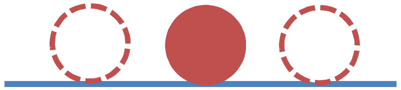
Introduction

Stability Analysis

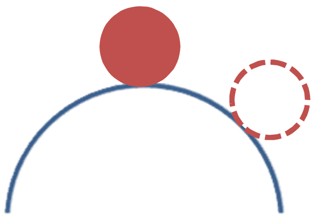
Static



stable

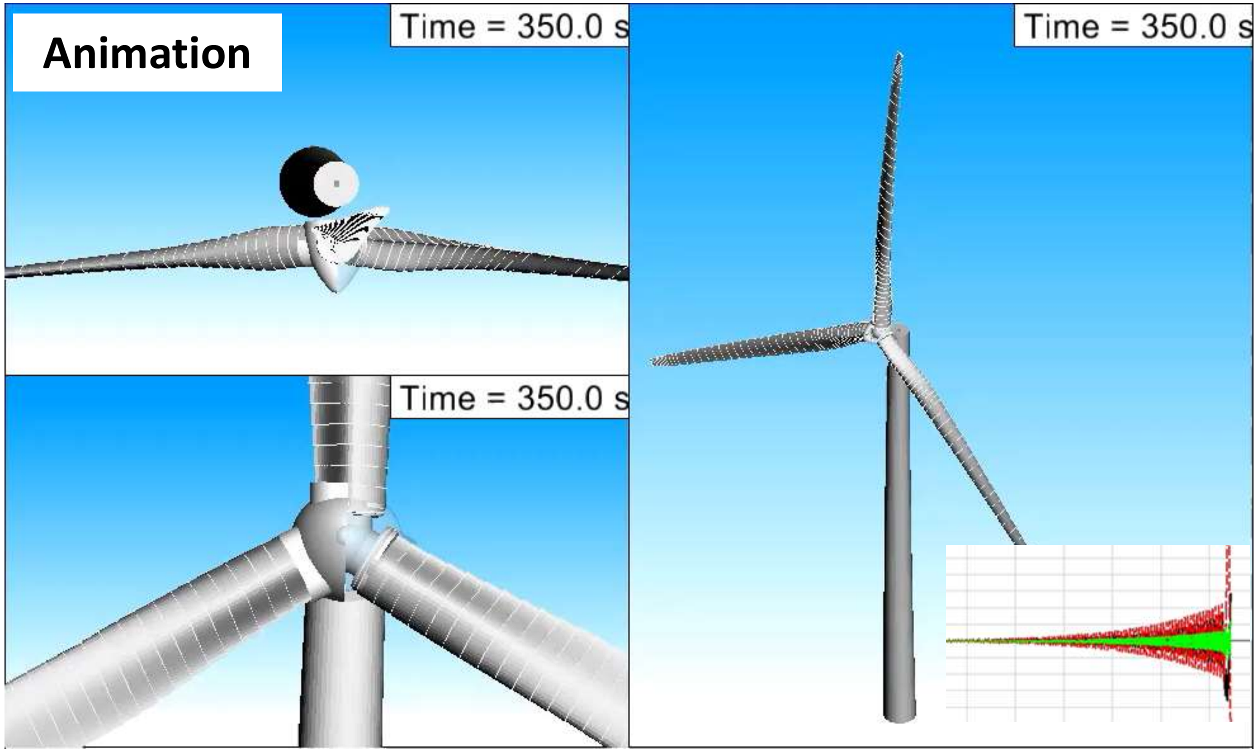


indifferent



unstable

Dynamic



unstable

Introduction

Dynamic stability analysis of (aero-)mechanical systems

- Methods presented here can be applied to any mechanical systems
- Includes solution for linear time-periodic systems
- Based on the state-space model

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Aeroelastic Stability Analysis of Wind Turbines

What are possible dynamic instabilities?

- Rotor blades classical flutter
- Controller induced instabilities
- (Aero-) mechanical instabilities (coupling of rotor modes with rotor shaft or tower)
- Rotor whirl flutter
- Stall induced instabilities*
- Vortex shedding induced vibration (wind turbines at parked condition)*

* these instabilities can't be analyzed with the methods presented yet because of specific demands of aerodynamic modelling

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Aeroelastic Stability Analysis of Wind Turbines

Why does stability analysis become more important?

- Larger wind turbines lead to more flexible structures
- Innovative control strategies have strong interaction with WT dynamics
- Observation of strong vibrations or instabilities at commercial wind turbines

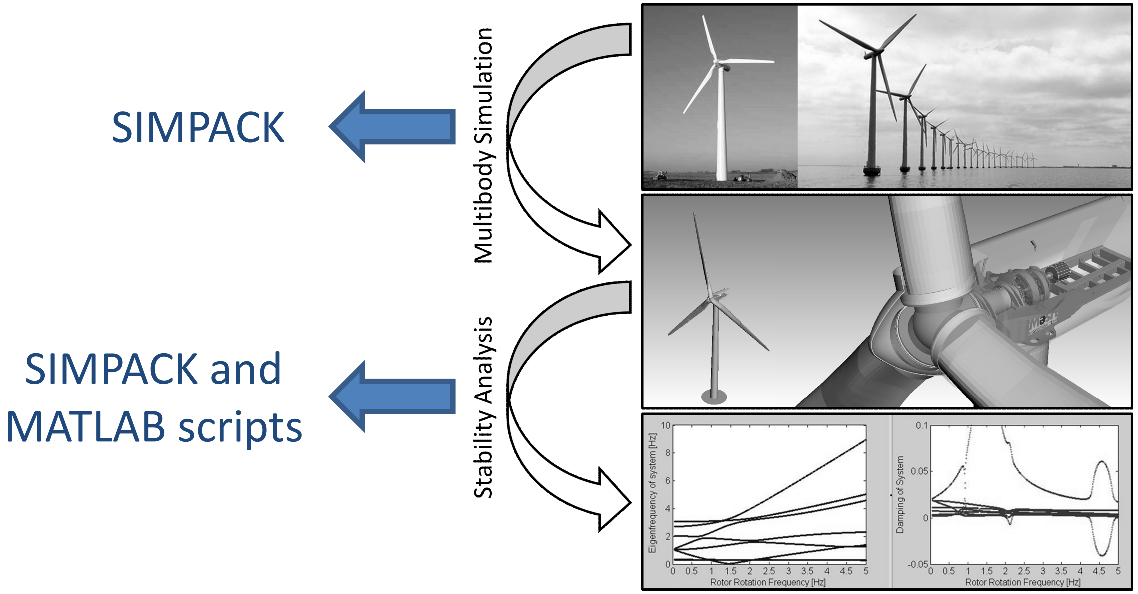
Future wind turbine designs will likely be stability-driven in contrast to the current loads-driven designs [1] and possibly stability analysis will become part of certification

[1] G. Bir, J. Jonkman, Aeroelastic Instabilities of Large Offshore and Onshore Wind Turbines, Conference Paper NREL/CP-500-41804, August 2007

Developed Stability Analysis Tool

Stability analysis tool for industrial applications:

- Based on multibody simulation
- To verify and predict possible instabilities and calculate safety margins
- Analyze the effects of different model parameters on the instability



Developed Stability Analysis Tool

Stability analysis of time-periodic systems:

- Determination of periodic equilibrium
- Linearization at the periodic equilibrium
- Classical eigenvalue analysis of linear system matrix is not valid
- Needs special methods and mathematical processes

Two selected methods:

Multiblade Coordinate Transformation	Application of Floquet theory
systems with rotors (e.g. wind turbines, helicopters)	all types of time-periodic systems
valid for linear and non-linear systems	valid for linear systems→ linearization
based on state-space matrices→ linearization	based on state-space matrices
aerodynamics in state-space model	aerodynamics in state-space model

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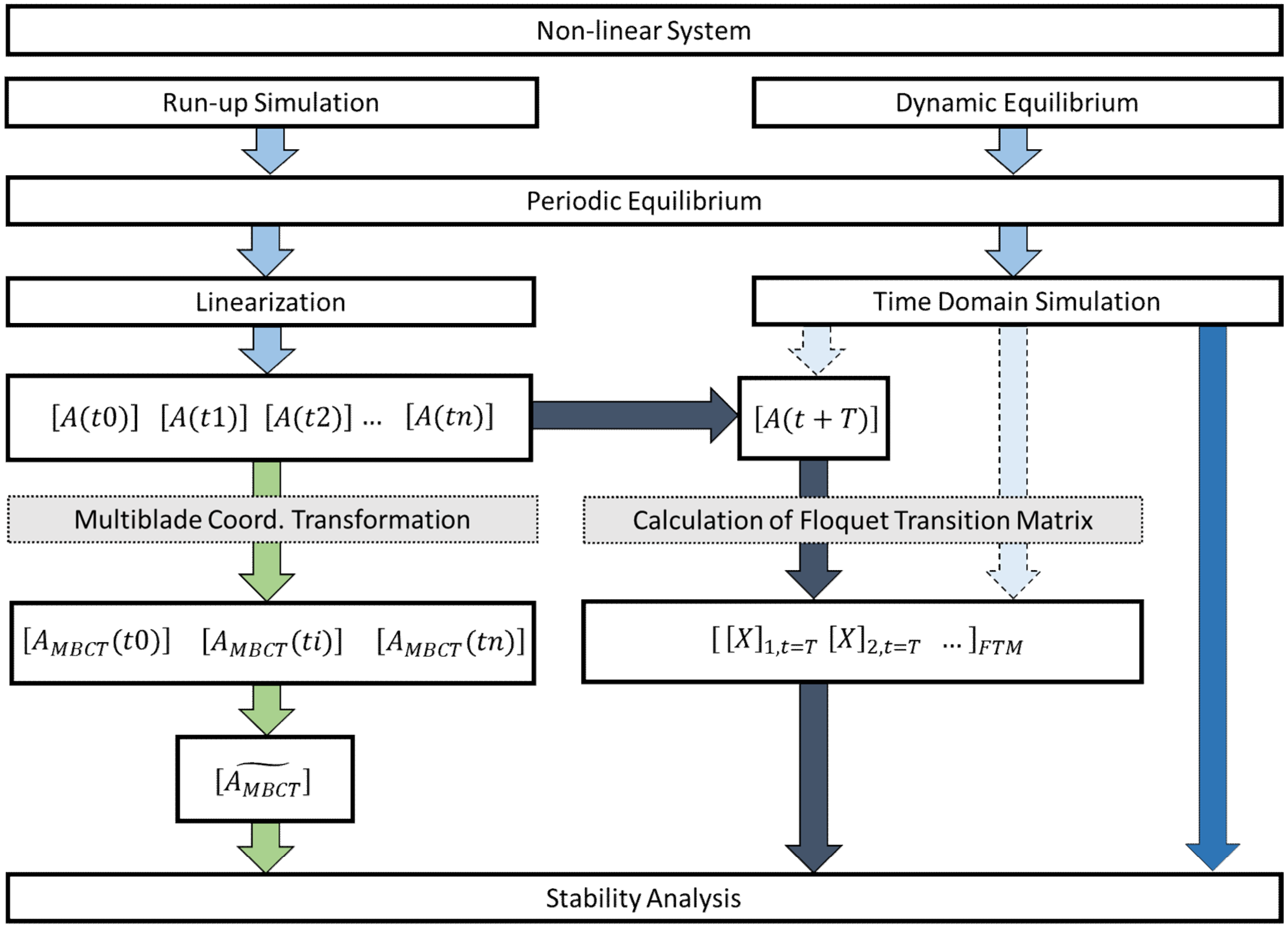
Developed Stability Analysis Tool

Current developed stability analysis approaches:



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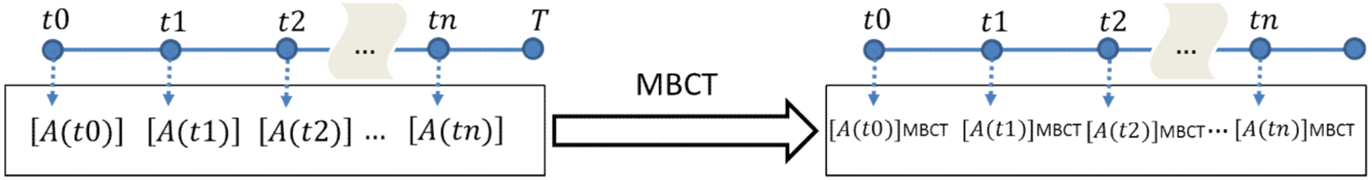
Developed Stability Analysis Tool

Method: Multiblade Coordinate Transformation (MBCT)

1) Time discrete linear system matrices are transformed into the new coordinates



$$\begin{bmatrix}[\dot{X}]_{tower}\\ [\dot{X}]_{blade\,1}\\ [\dot{X}]_{blade\,2}\\ [\dot{X}]_{blade\,3}\end{bmatrix} = [A]\cdot\begin{bmatrix}[X]_{tower}\\ [X]_{blade\,1}\\ [X]_{blade\,2}\\ [X]_{blade\,3}\end{bmatrix} \xrightarrow{\text{multiblade coordinate transformation}} \begin{bmatrix}[\dot{X}]_{tower}\\ [\dot{X}]_{MBC\_0}\\ [\dot{X}]_{MBC\_1c}\\ [\dot{X}]_{MBC\_1s}\end{bmatrix} = [A]_{MBCT}\cdot\begin{bmatrix}[X]_{tower}\\ [X]_{MBC\_0}\\ [X]_{MBC\_1c}\\ [X]_{MBC\_1s}\end{bmatrix}$$

$$[X]_{blade\,1} = \begin{bmatrix}x1\\ \vdots\\ xn\end{bmatrix}_{blade\,1}$$

$$[X]_{MBC-0} = \frac{[X]_{blade\,1} + [X]_{blade\,2} + [X]_{blade\,3}}{3}$$

$$[X]_{MBC-1c} = \frac{2}{3}\sum_{i=1}^{3}([X]_{blade\,i}) \times cos\left(\psi + (i-1)\frac{2\pi}{3}\right)$$

$$[X]_{MBC-1s} = \frac{2}{3}\sum_{i=1}^{3}([X]_{blade\,i}) \times sin\left(\psi + (i-1)\frac{2\pi}{3}\right)$$

2) Stability analysis: evaluation of eigenvalues of time-averaged transformed system matrices

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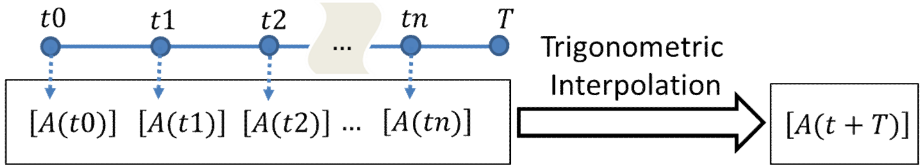
Developed Stability Analysis Tool

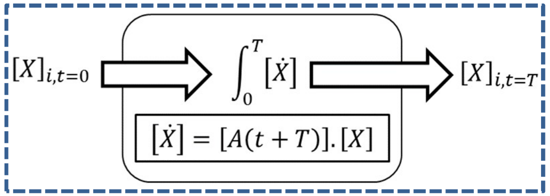
Method: Application of Floquet theory

1) Fourier interpolation to calculate the periodic system matrix



2) n (number of states) independent initial state vectors are selected

3) Time integration with n initial state vectors



4) Floquet transition matrix (FTM) is then calculated using:

$$[X]_{t=T} = [FTM] \times [X]_{t=0}$$

5) Stability analysis: evaluation of eigenvalues of Floquet transition matrix (characteristic multipliers)

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Stability Analysis of a Reference Wind Turbine

Example: 5 MW reference wind turbine [1], Simpack V9.10

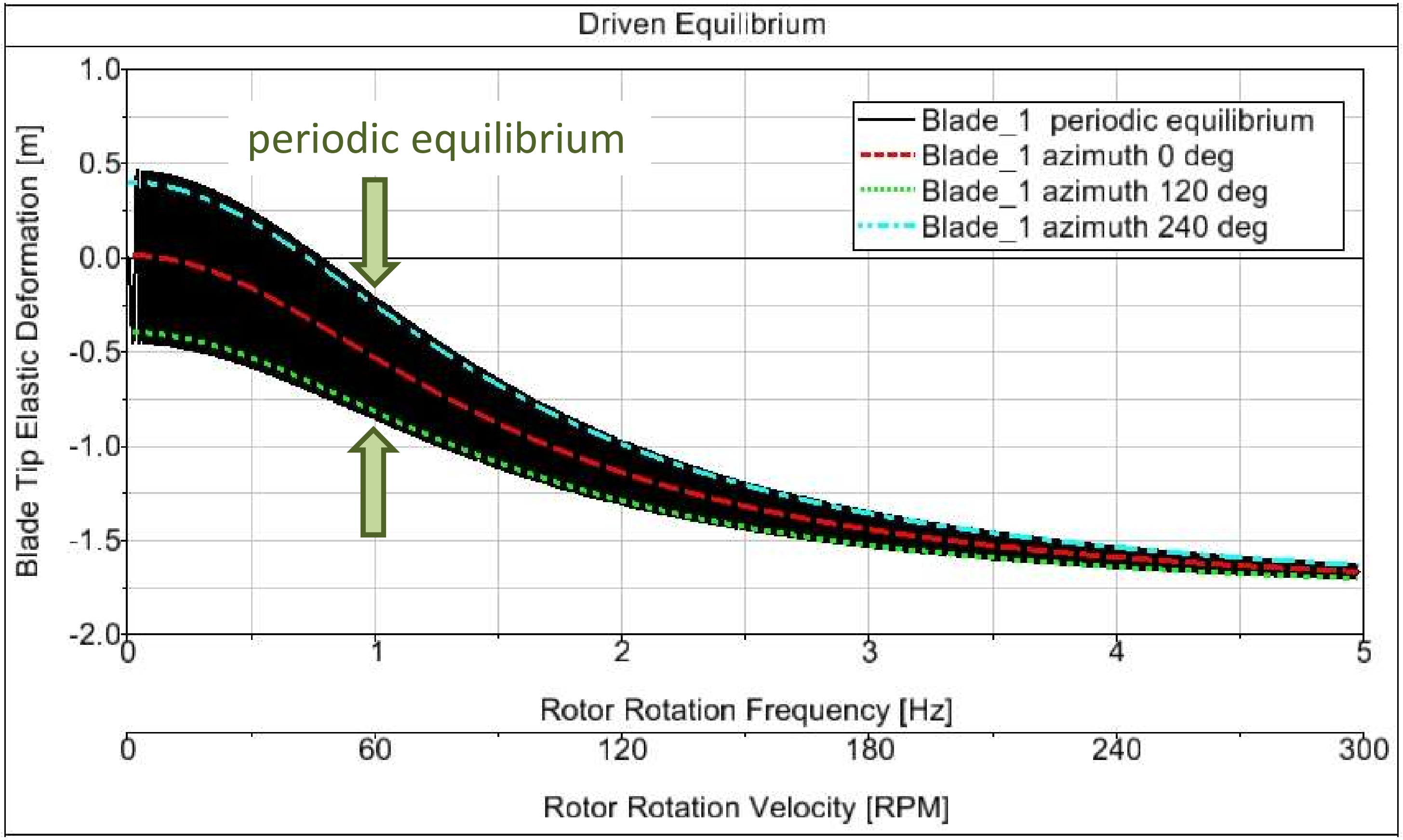
	Stability Analysis	
	Mechanical	**Aeroelastic**
Model	model 1	model 2
Blade (SIMBEAM) 2% structural damping	modal DOF: 1st in-plane bending	modal DOF: 1st to 4th out of plane bending 1st, 2nd in-plane bending 1st torsion
Tower (SIMBEAM) 1% structural damping	modal DOF: 1st, 2nd side-to-side 1st, 2nd fore-aft 1st torsion	modal DOF: 1st, 2nd side-to-side 1st, 2nd fore-aft 1st torsion
Aerodynamic	-	AeroDyn

[1] J.Jonkman, S.Butterfield, W.Musial, G.Scott, Definition of a 5-MW Reference Wind Turbine for Offshore System Development, Technical Report, NREL/TP-500-38060, February 2009

Stability Analysis of a Reference Wind Turbine

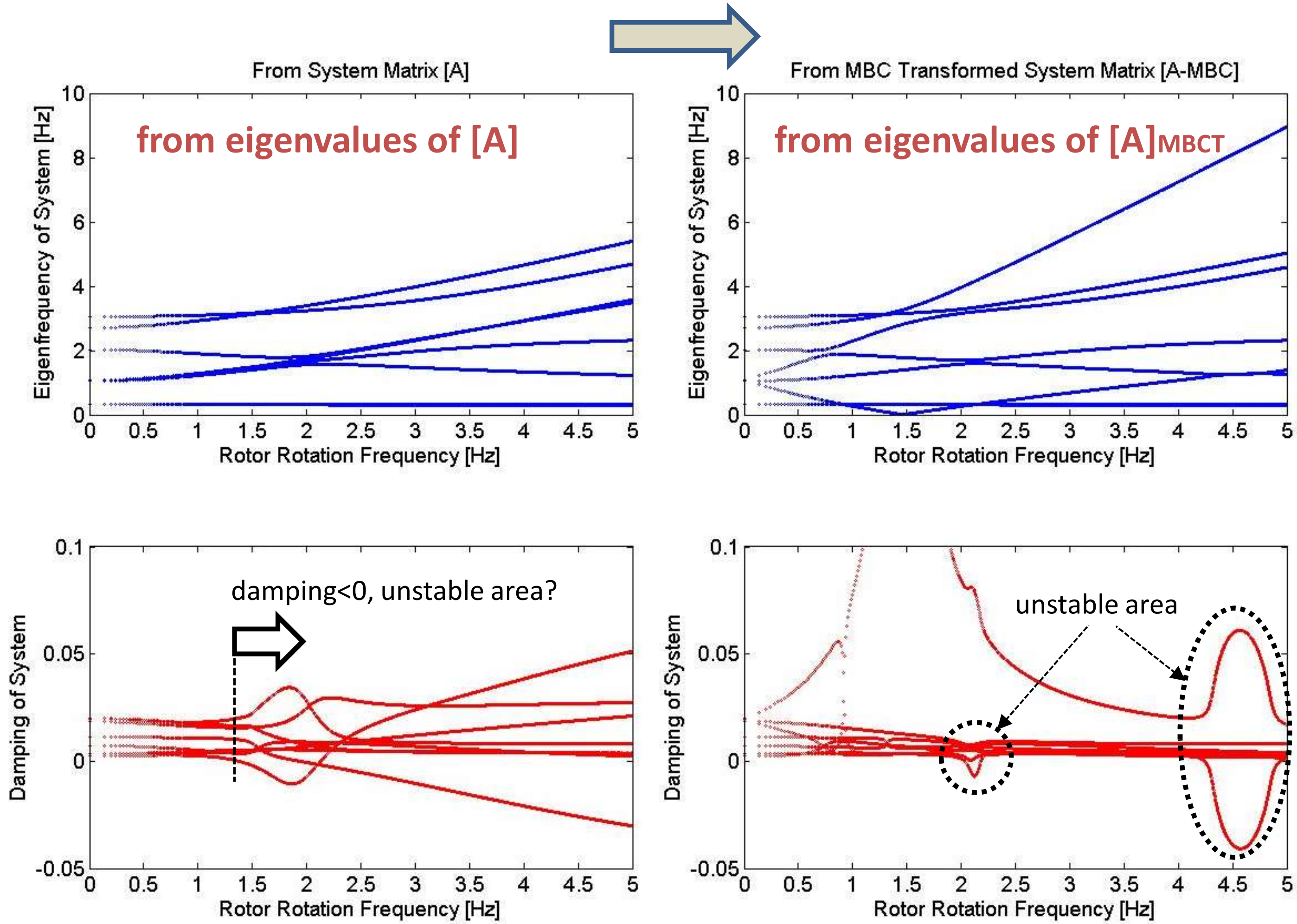
Calculation of equilibrium (model 1): periodic solution

Equilibrium states for the different rotor rotation velocities and azimuthal positions ⇨ states for the linearization



Stability Analysis of a Reference Wind Turbine

Using multiblade coordinate transformation (model 1)



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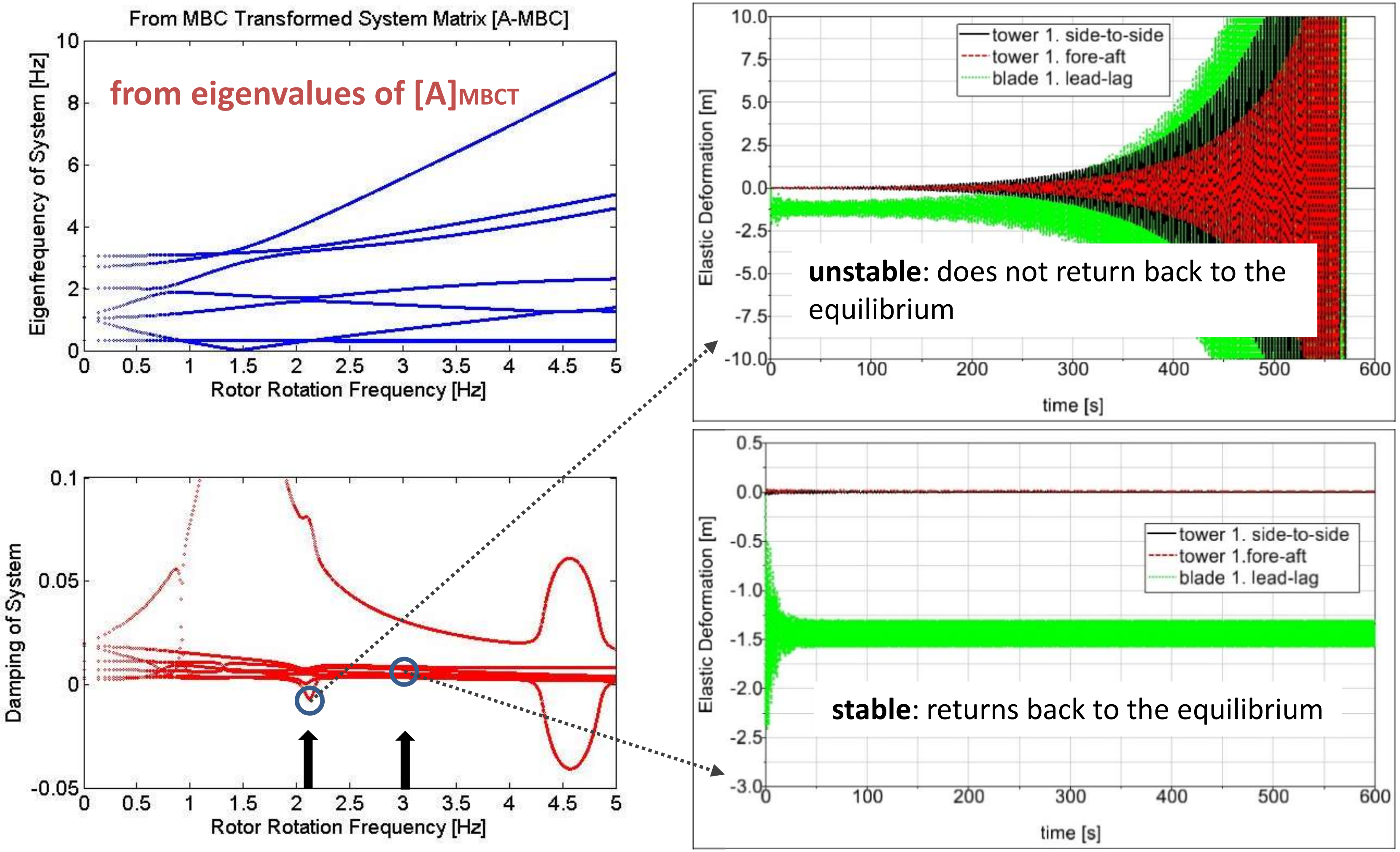
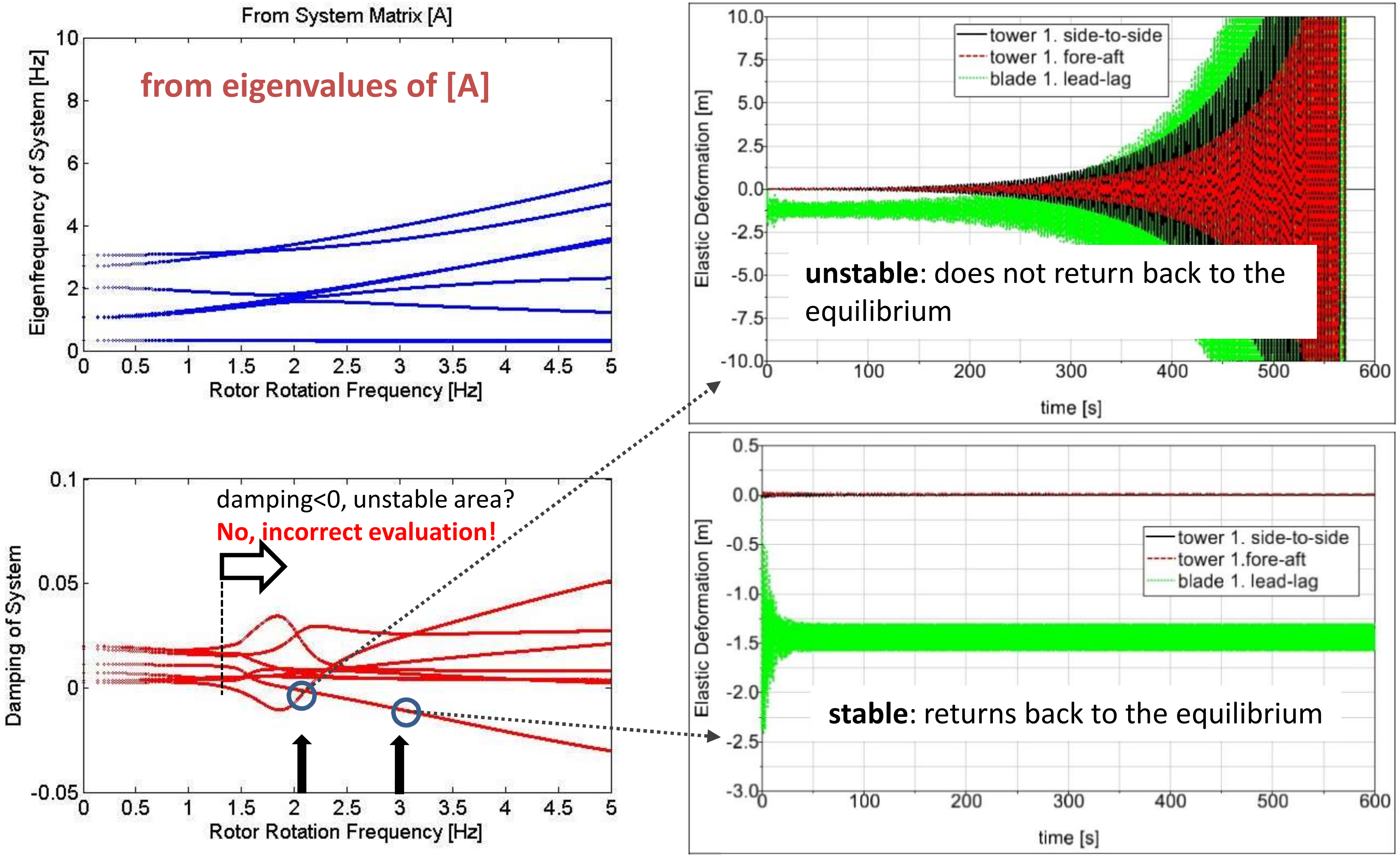
Stability Analysis of a Reference Wind Turbine

Verification of results using time domain simulation (model 1)



Stability Analysis of a Reference Wind Turbine

Verification of results using time domain simulation (model 1)



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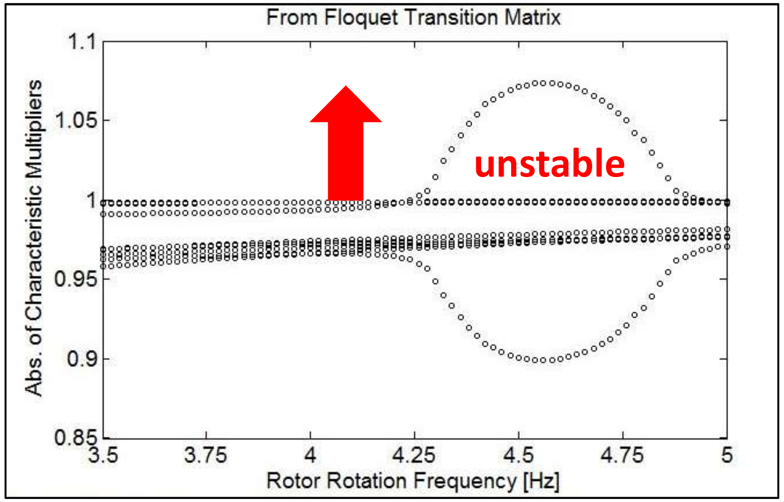
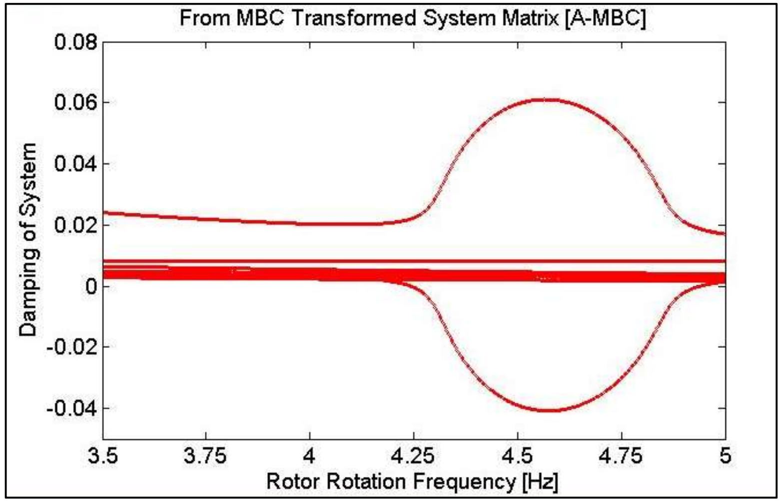
Stability Analysis of a Reference Wind Turbine

Using Floquet theory (model 1)

Comparison of stability prediction, Floquet vs. MBCT





	Floquet	MBCT
Instability criterion	characteristic multipliers*>1	damping<0

* characteristic multipliers: magnitudes of eigenvalues of Floquet transition matrix

Stability Analysis of a Reference Wind Turbine

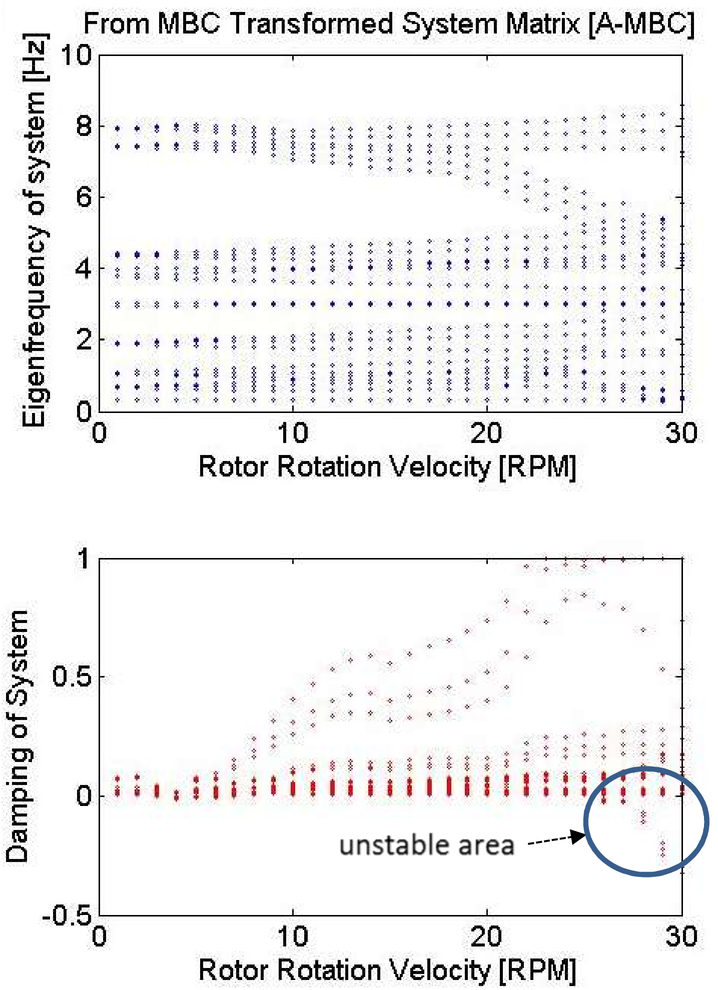
Aeroelastic stability (model 2)

uniform axial stream

V_{wind} = 11.4 [m/s]

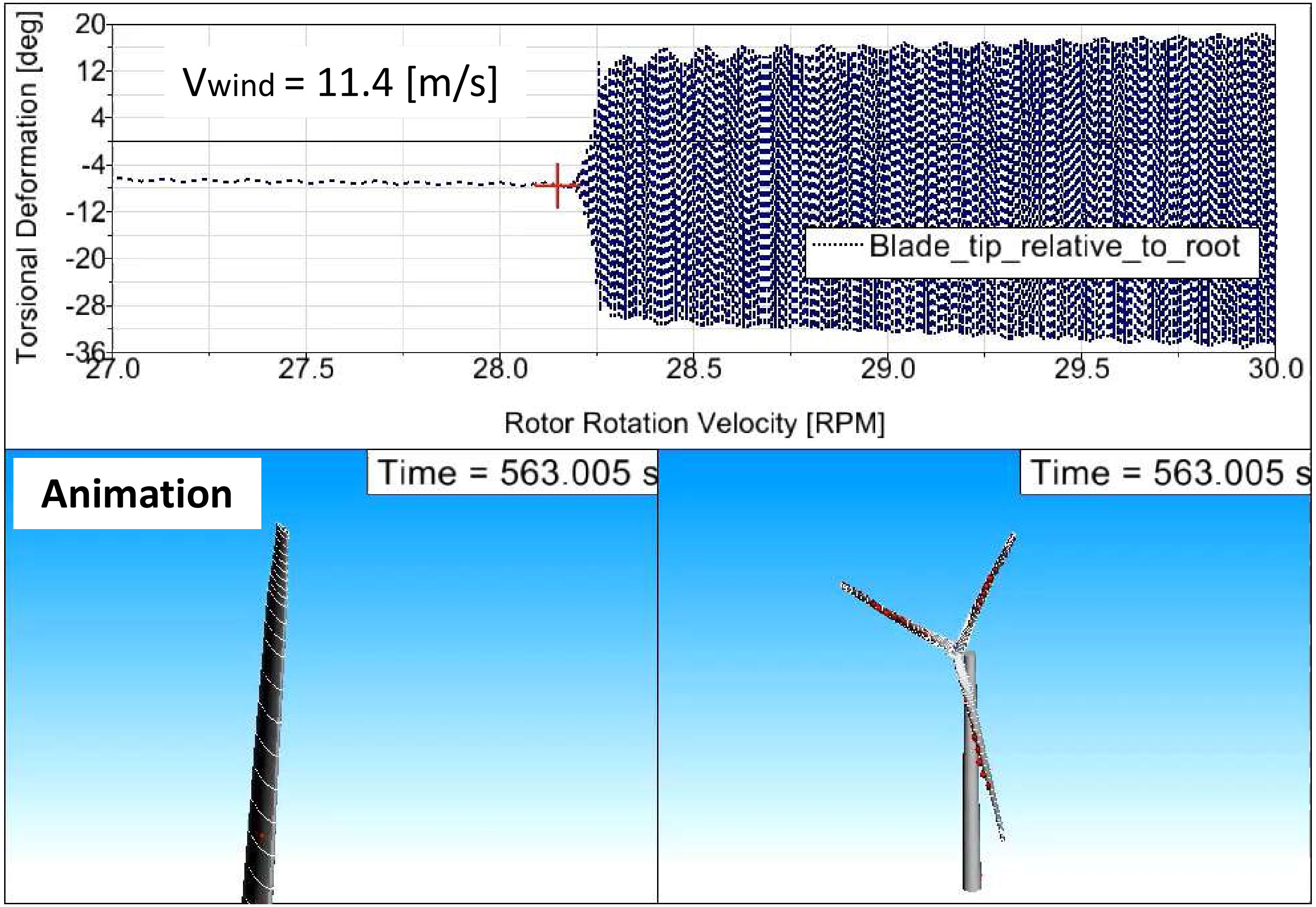
blade pitch angle Θ = 0 [deg]

Ω = 0 to 30 [RPM]



Stability Analysis of a Reference Wind Turbine

Verification of the predicted aeroelastic instability (model 2)



Conclusions and Current Work

Conclusions:

- Different methods for the stability analysis based on general purpose multibody simulation software have been developed and successfully demonstrated.
- Stability tool is now available for customer applications.
- A mechanical instability of an exemplary reference wind turbine could be **predicted** using multiblade coordinate transformation or Floquet theory and was **verified** by time domain simulation.
- Aeroelastic stability analysis of the reference wind turbine shows an instability by run-up simulation at constant wind speed.

Current work:

- Further development of the stability analysis tool.
- Application of the developed methods in other engineering fields.

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