Symbolic Flexible Multibody Models for Wind Turbine Controller Design and Analysis

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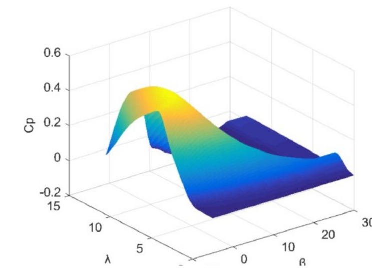
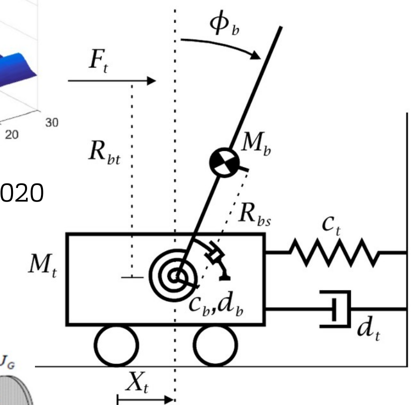
Motivation

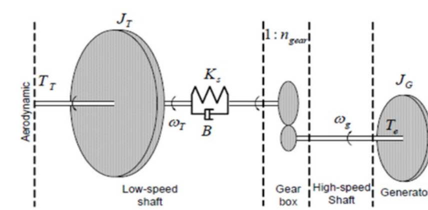
- Wind turbine development relies on models
  - Esp. simplified dynamic models
  - Various levels of fidelity, depending on task
- Currently, usually one-off developments for a specific purpose
  - Based on a heuristic structure and simplifications
  - Or linearizations from high detail simulators
- Change management and traceability difficult
- **One source for whole family of models desirable**



Araghi 2020



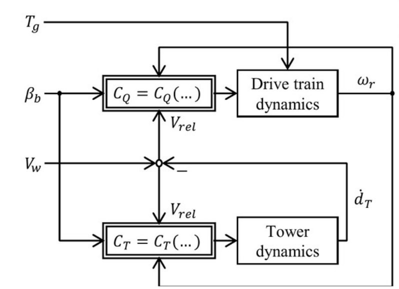
Jassmann et al. 2016



Bassi and Mobarak, 2017

$$\begin{bmatrix} \dot{\omega}_t \\ \dot{\omega}_g \\ \dot{T}_{tw} \\ \dot{T}_g \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{N_g}{J_t} & 0 & 0 \\ 0 & 0 & \frac{1}{J_g} & -\frac{1}{J_g} & 0 \\ K_s N_g & -K_s & -\left(\frac{N_g^2 B_s}{J_t} + \frac{B_s}{J_g}\right) & \frac{B_s}{J_g} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau_g} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \begin{bmatrix} \omega_t \\ \omega_g \\ T_{tw} \\ T_g \\ \beta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{\tau_g} & 0 \\ 0 & \frac{1}{\tau} \end{bmatrix} \begin{bmatrix} T_{g,ref} \\ \beta_{ref} \end{bmatrix} + \begin{bmatrix} \frac{1}{J_t} \\ 0 \\ \frac{N_g B_s}{J_t} \\ 0 \\ 0 \end{bmatrix} T_t$$

Ghanbarpour et al 2020



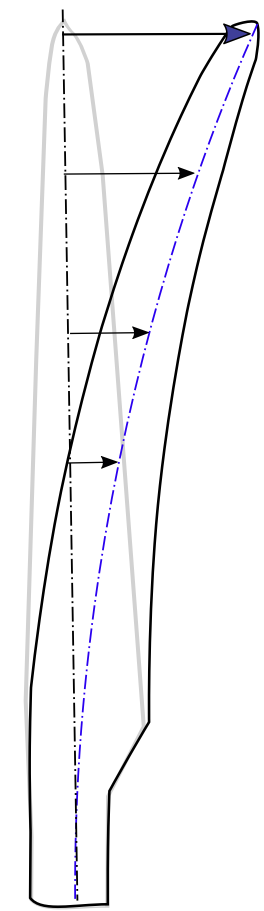
Löw and Obradovic 2018

Modular Modeling with Kane's Method

- Formalism for deriving **generalized equations of motion**
  - No constraint equations
  - Only as many ODEs as DOF
- Intuitive, modular definition of the System
  - User defines pose and inertial parameters per body
  - Automatic formulation of Newton-Euler-equations
  - Automatic removal of constraints
  - Enabled by powerful computer algebra systems (CAS)
- Symbolic equations of motion
  - Variable (symbolic) parameters
  - Can be further processed in many different ways

Elastic / Flexible Bodies

- Floating frame of reference
- Superposition of rigid (undeformed) and flexible body motion
- Flexible coordinates may be finite elements or modes
- Standard Input Data (SID due to Schwertassek and Wallrapp)
  - Linear-quadratic representation
  - Includes centrifugal stiffening and gravitational softening
  - Standardized data format for interfacing FEM tools with dynamic modeling tools
  - Offloading of computations to pre-simulation stage
  - Supported e.g. by ANSYS and Simpack



Results

- Comparison of three model variations with OpenFAST
  - 6 DOF: tower fore-aft & side-side, generator & hub speed, collective blade flap- & edge-wise
  - 4 DOF: tower fore-aft, generator & hub speed, collective blade flap-wise
  - 2 DOF: tower fore-aft, hub speed
  - All blade motions are collective

Results – 6DOF Model

```
/* 1 Tower */
load(filename_merge(load_pathname, "tw_sid.mac"));
elastic_dof[1]: [q[1], q[2]];
ebody[1]: tower;
T0G[1]: Tdisp(0, 0, 0);

/* 2 Nacelle */
mass[2]: NacMass;
Ixx[2]: NacXIner;
Iyy[2]: NacYIner;
Izz[2]: NacZIner;
BodyRef[2]: 1;
/* TrefG[2]: Tdisp(q[1], q[2], 0).Tdisp(NacCMxn, NacCMyn, NacCMzn); */
TrefG[2]: Telast(1, 1).Tdisp(NacCMxn, NacCMyn, NacCMzn);
/* TrefG[2]: Tdisp(q[1], q[2], 0).Tdisp(NacCMxn, NacCMyn, NacCMzn).Troty_lin(q[1]*TwTrans2Roll).Trotx_lin(-q[2]*TwTrans2Roll); */

/* 3 Hub */
mass[3]: HubMass;
Ixx[3]: HubIner;
Iyy[3]: HubIner;
Izz[3]: HubIner;
BodyRef[3]: 2;
TrefG[3]:  Tdisp(HubCM+OverHang-NacCMxn, -NacCMyn, Twr2Shft-NacCMzn).Trotx(q[3]);

/* 4,5,6 Blades */
load(filename_merge(load_pathname, "bd_sid.mac"));

/* Blade 1 */
elastic_dof[4]: [q[4], q[5]];
ebody[4]: blade;
BodyRef[4]: 3;
TrefG[4]:  Tdisp(-HubCM, 0, 0).Trotz(theta);

/* Blade 2 */
elastic_dof[5]: [q[4], q[5]];
```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Results – Generalized Equations of Motion

$$
\begin{bmatrix}
\ddot{q}_1\, m_{e,\text{tow},0}[1,1] + q_1\, K_{e,\text{tow},0}[1,1] + \dot{q}_1\, D_{e,\text{tow},0}[1,1] + q_1\, g\, C_{t,\text{tow},1}[1,1,3] + \left(-3\,\ddot{q}_5\, C_{t,\text{bld},0}[2,2] - 3\,\ddot{q}_4\, C_{t,\text{bld},0}[1,2]\right)\, \sin\vartheta + \ldots \\
+ \left(3\,\ddot{q}_5\, C_{t,\text{bld},0}[2,1] + 3\,\ddot{q}_4\, C_{t,\text{bld},0}[1,1]\right)\, \cos\vartheta + 3\,\ddot{q}_1\, m_{\text{bld}} + \ddot{q}_1\, m_{\text{nac}} + \ddot{q}_1\, m_{\text{hub}} - F_{\text{hub}} \\
\\
\ddot{q}_2\, m_{e,\text{tow},0}[2,2] + q_2\, K_{e,\text{tow},0}[2,2] + \dot{q}_2\, D_{e,\text{tow},0}[2,2] + q_2\, g\, C_{t,\text{tow},1}[2,2,3] + 3\,\ddot{q}_2\, m_{\text{bld}} + \ddot{q}_2\, m_{\text{nac}} + \ddot{q}_2\, m_{\text{hub}} \\
\\
\frac{1}{i_{\text{gear}}}\left(\left(3\,\ddot{q}_3\, i_{\text{gear}}\, I_{e,\text{bld},0}[2,2] - 3\,\ddot{q}_3\, i_{\text{gear}}\, I_{e,\text{bld},0}[1,1]\right)\, \sin^2\vartheta + \ldots\right. \\
+ \left(-3\,\ddot{q}_5\, i_{\text{gear}}\, Cr_{e,\text{bld},0}[2,2] - 3\,\ddot{q}_4\, i_{\text{gear}}\, Cr_{e,\text{bld},0}[1,2]\right)\, \sin\vartheta + \left(3\,\ddot{q}_5\, i_{\text{gear}}\, Cr_{e,\text{bld},0}[2,1] + 3\,\ddot{q}_4\, i_{\text{gear}}\, Cr_{e,\text{bld},0}[1,1]\right)\, \cos\vartheta + \ldots \\
\left.+3\,\ddot{q}_3\, i_{\text{gear}}\, I_{e,\text{bld},0}[1,1] - i_{\text{gear}}\, Trot + \ddot{q}_3\, i_{\text{gear}}\, HubIner + \left(q_3\, K_{\text{hub,gen}} + \dot{q}_3\, D_{\text{hub,gen}}\right)\, i_{\text{gear}} - q_6\, K_{\text{hub,gen}} - \dot{q}_6\, D_{\text{hub,gen}}\right) \\
\\
\left(3\,\dot{q}_3^2\, q_5\, O_{e,\text{bld},1}[2,1,2] + 3\,\dot{q}_3^2\, q_4\, O_{e,\text{bld},1}[1,1,2]\right)\, \sin^2\vartheta + \ldots \\
+ \left(\left(-3\,\dot{q}_3^2\, q_5\, O_{e,\text{bld},1}[2,1,4] - 3\,\dot{q}_3^2\, q_4\, O_{e,\text{bld},1}[1,1,4]\right)\, \cos\vartheta - 3\,\ddot{q}_1\, C_{t,\text{bld},0}[1,2] - 3\,\ddot{q}_3\, Cr_{e,\text{bld},0}[1,2]\right)\, \sin\vartheta + \ldots \\
+ \left(3\,\dot{q}_3^2\, q_5\, O_{e,\text{bld},1}[2,1,1] + 3\,\dot{q}_3^2\, q_4\, O_{e,\text{bld},1}[1,1,1]\right)\, \cos^2\vartheta + \ldots \\
+ \left(3\,\ddot{q}_1\, C_{t,\text{bld},0}[1,1] + 3\,\ddot{q}_3\, Cr_{e,\text{bld},0}[1,1]\right)\, \cos\vartheta - 3\, F_{e,\text{flap}} + \ldots \\
+3\,\ddot{q}_5\, m_{e,\text{bld},0}[1,2] + 3\,\ddot{q}_4\, m_{e,\text{bld},0}[1,1] + 3\, q_5\, K_{e,\text{bld},0}[1,2] + 3\, q_4\, K_{e,\text{bld},0}[1,1] + 3\,\dot{q}_4\, D_{e,\text{bld},0}[1,1] \\
\\
\left(3\,\dot{q}_3^2\, q_5\, O_{e,\text{bld},1}[2,2,2] + 3\,\dot{q}_3^2\, q_4\, O_{e,\text{bld},1}[1,2,2]\right)\, \sin^2\vartheta + \ldots \\
+ \left(\left(-3\,\dot{q}_3^2\, q_5\, O_{e,\text{bld},1}[2,2,4] - 3\,\dot{q}_3^2\, q_4\, O_{e,\text{bld},1}[1,2,4]\right)\, \cos\vartheta - 3\,\ddot{q}_1\, C_{t,\text{bld},0}[2,2] - 3\,\ddot{q}_3\, Cr_{e,\text{bld},0}[2,2]\right)\, \sin\vartheta + \ldots \\
+ \left(3\,\dot{q}_3^2\, q_5\, O_{e,\text{bld},1}[2,2,1] + 3\,\dot{q}_3^2\, q_4\, O_{e,\text{bld},1}[1,2,1]\right)\, \cos^2\vartheta + \ldots \\
+ \left(3\,\ddot{q}_1\, C_{t,\text{bld},0}[2,1] + 3\,\ddot{q}_3\, Cr_{e,\text{bld},0}[2,1]\right)\, \cos\vartheta - 3\, F_{e,\text{edge}} + 3\,\ddot{q}_5\, m_{e,\text{bld},0}[2,2] + \ldots \\
+3\,\ddot{q}_4\, m_{e,\text{bld},0}[2,1] + 3\, q_5\, K_{e,\text{bld},0}[2,2] + 3\, q_4\, K_{e,\text{bld},0}[2,1] + 3\,\dot{q}_5\, D_{e,\text{bld},0}[2,2] \\
\\
\frac{i_{\text{gear}}\, T_{\text{gen}} + \ddot{q}_6\, i_{\text{gear}}\, I_{\text{gen}} + \left(-q_3\, K_{\text{hub,gen}} - \dot{q}_3\, D_{\text{hub,gen}}\right)\, i_{\text{gear}} + q_6\, K_{\text{hub,gen}} + \dot{q}_6\, D_{\text{hub,gen}}}{i_{\text{gear}}}
\end{bmatrix}
$$

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  - 4 DOF: tower fore-aft, generator & hub speed, collective blade flap-wise
  - 2 DOF: tower fore-aft, hub speed
  - All blade motions are collective
- Standalone, high performance simulation program
  - Special rotor effective aerodynamics model with damping and blade mode excitation
  - Interface to DISCON.dll
  - Read OpenFAST parameters and wind data (rotor effective)
  - Write OpenFAST binary output
- Simulation of wind steps up and down 1 m/s

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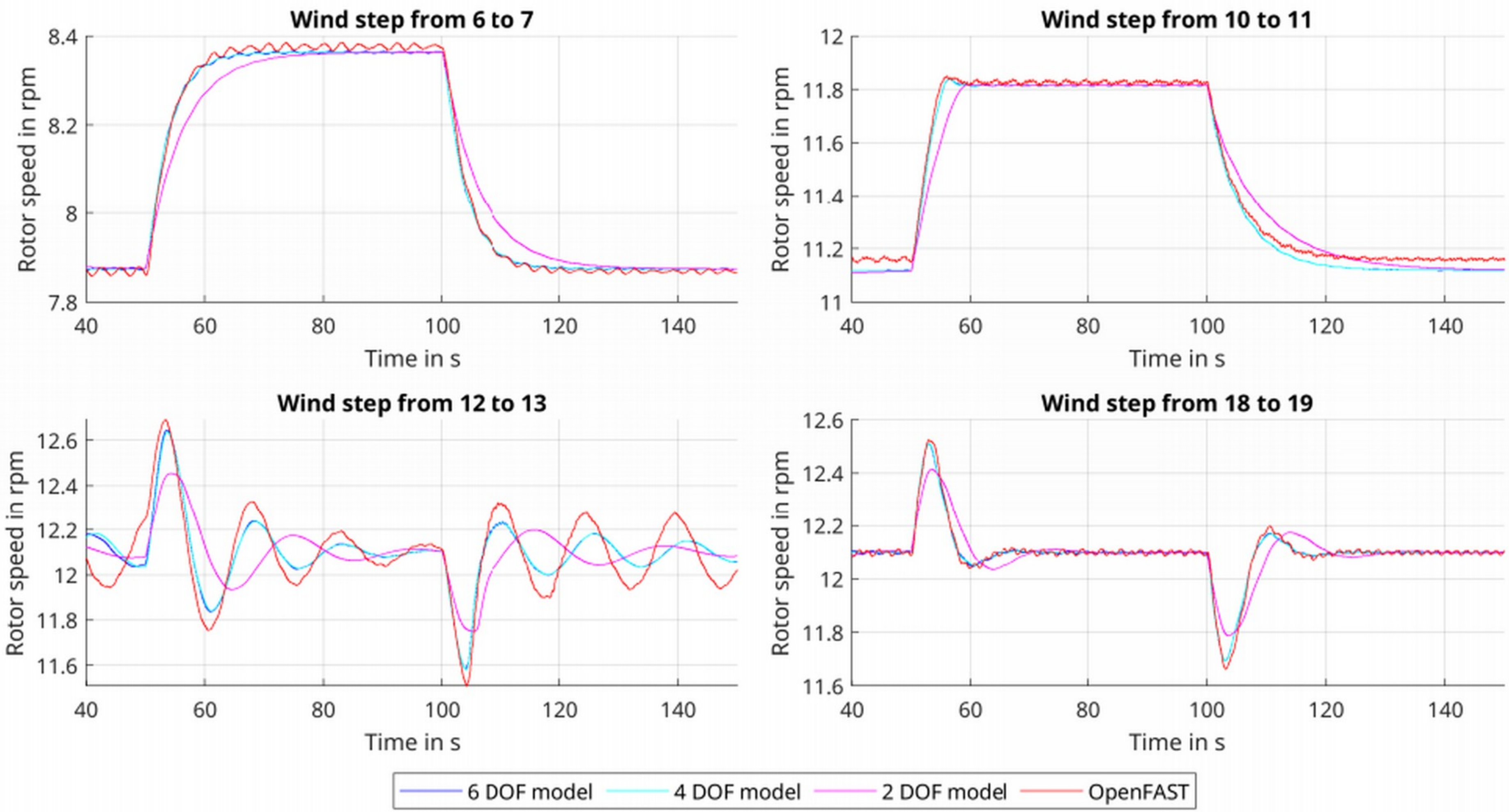
Results – Rotor Speed



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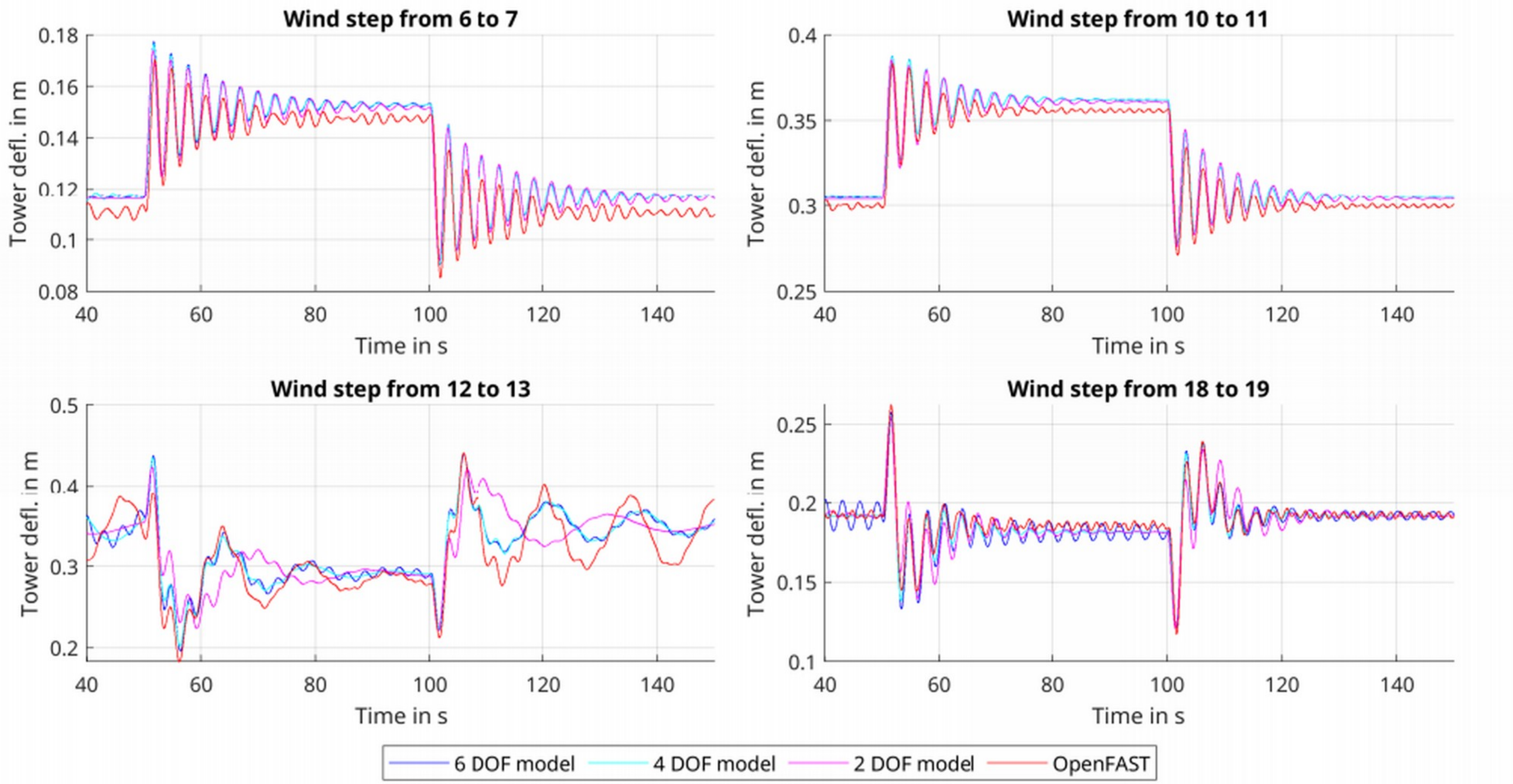
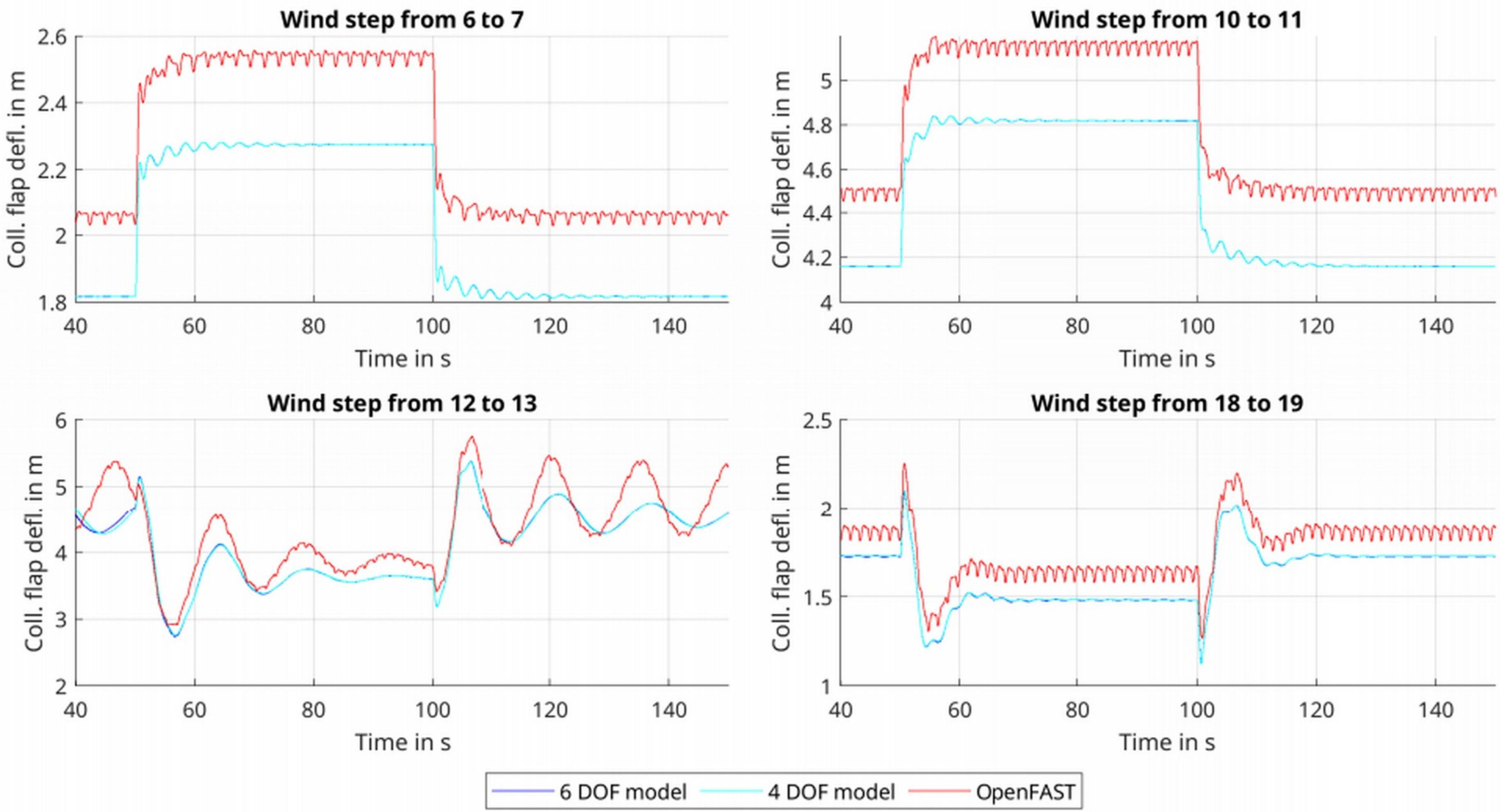
Results – Tower fore-aft Deflection

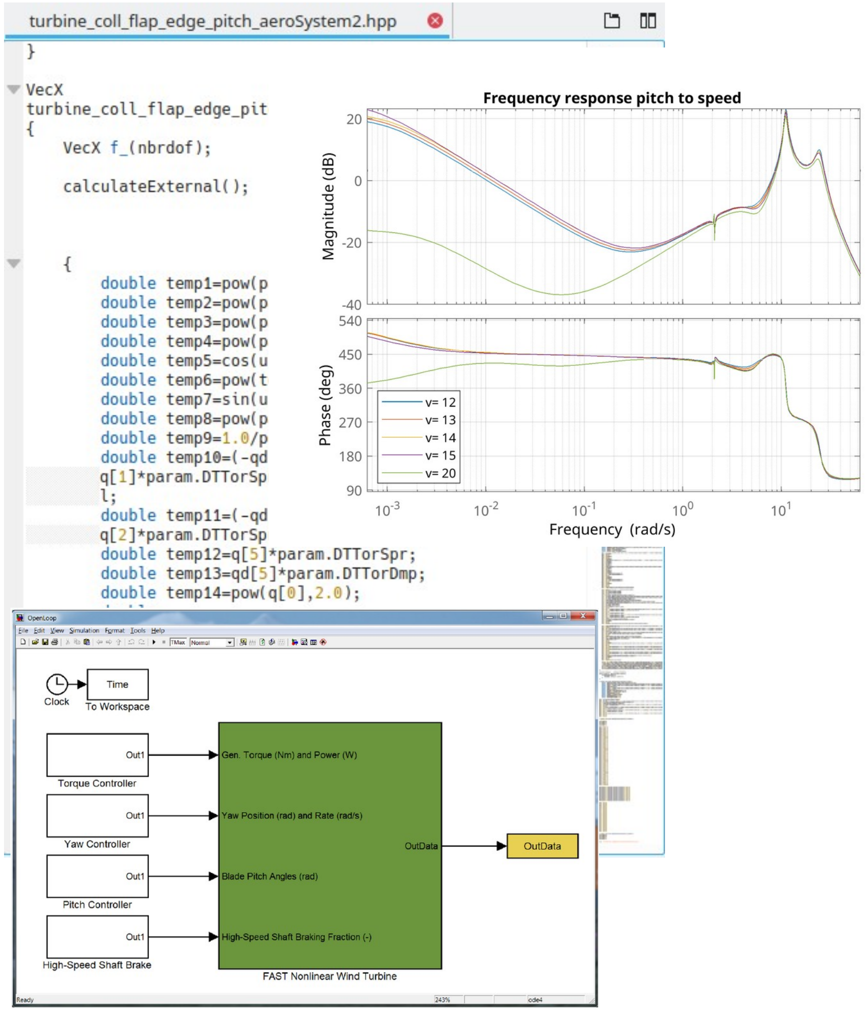


Results – Collective Blade Flap Deflection



Applications

- **Linear Models (all operating points at once)**
  - Classical Controller Design
  - Frequency domain analysis
  - Matrix inequality based control design
- **Simulations models, Digital Twins**
- **Jacobians for advanced observer and controller design**
  - Nonlinear Model Predictive Control
  - Extended Kalman Filters
  - Moving Horizon Estimators
- **Sensitivities for parameter studies and optimization**
- **Generation of custom, high performance code for all these applications**



Jonkmann and Jonkmann 2016

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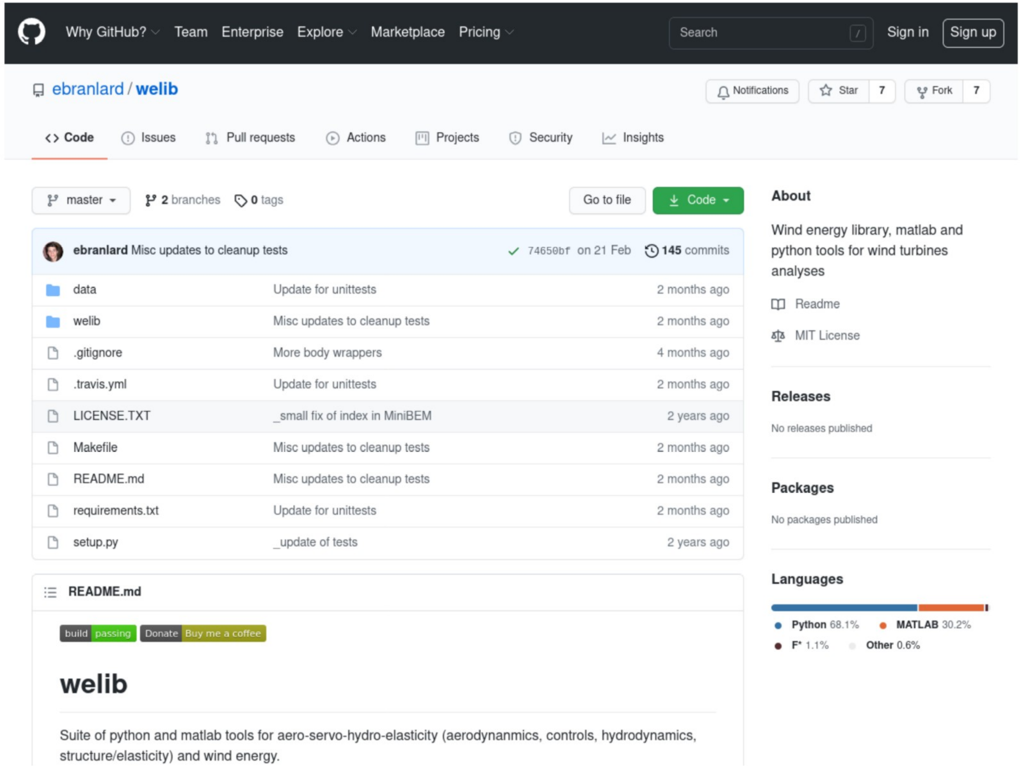
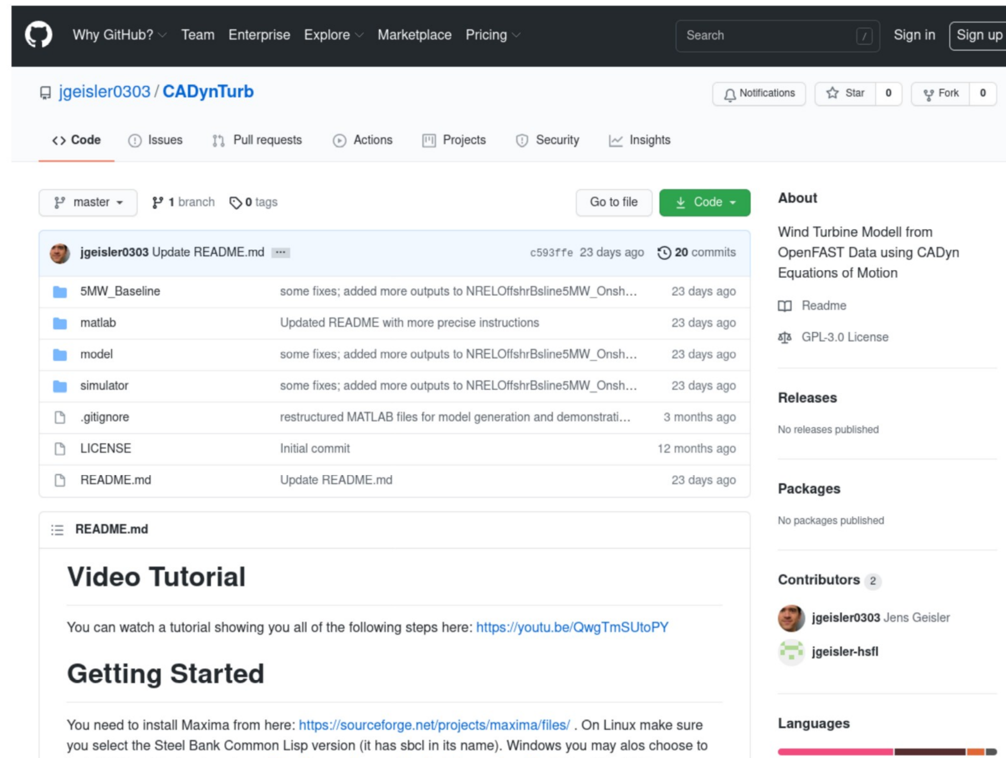
- WeLib – Wind Library
  - https://github.com/ebranlard/welib
  - Python code
  - Extensive library covering a wide range of aspects
  - Including aero- and hydro-dynamics



The Frameworks

- CADyn – Computer aided Dynamics
  - https://github.com/jgeisler0303/CADynTurb
  - Maxima, MATLAB and C++ code
  - General purpose CADyn MB code plus specific turbine simulator
  - Supporting repositories CCBlade, FEMBeam



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Thank You for Your Interest!

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