High-fidelity time- and nonlinear frequency-domain analysis of unsteady loads of floating offshore wind turbines in yawed wind

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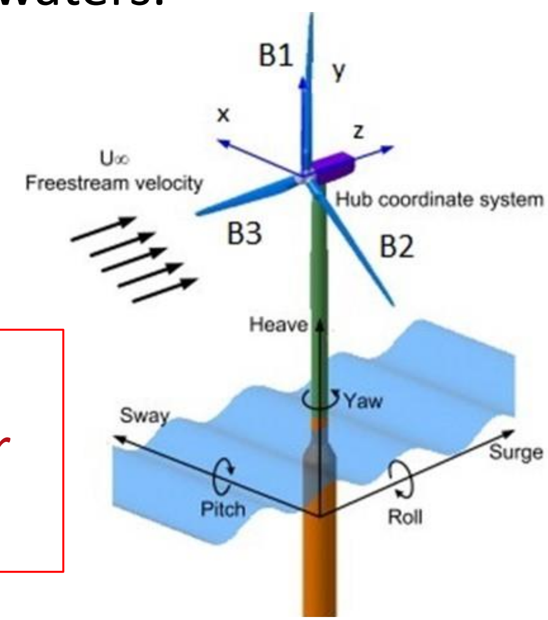
Background and Motivation

- Floating offshore wind turbines (FOWTs) enable tapping into stronger and more predictable wind.
- Appealing option for countries with limited shallow waters.
- FOWT development typically uses low-fidelity tools.
- Computational Fluid Dynamics (CFD) contributes to understanding FOWT aerodynamics [1,2].



Study's aims: investigate FOWT yawed aerodynamics and demonstrate potential of harmonic balance CFD for generating data for low-fidelity model improvements.

1. Ortolani, Persico, Drofelnik, Jackson, Campobasso, *Cross-comparative analysis of loads and power of pitching floating offshore wind turbine rotors using frequency-domain Navier-Stokes CFD and blade element momentum theory*, Journal of Physics: Conference Series, **1618(5**), ref. 052016,, 2020.

2. Ortolani, Papi, Bianchini, Persico, Drofelnik, M.S. Campobasso, *Multi-fidelity Analyses of Rotor Loads of Floating Offshore Wind Turbines with Wind/Wave Misalignment*, Journal of Physics: Conference Series, **2265**(4), ref. 042010, 2022.

Outline

- Numerical methods
- Kinematics of FOWT rotor grid for pitching in yawed wind
- Results
- Summary

Numerical methods

- AERODYN Blade Element Momentum Theory (BEMT) libraries used in NREL OpenFAST wind turbine code. Dynamic inflow used.
- ANSYS FLUENT incompressible code.
- Lancaster University massively parallel incompressible time- and nonlinear harmonic balance (frequency-domain) ARCTIC code [3], twin of COSA compressible code [4,5].

3. A. Cavazzini, M.S. Campobasso. M. Marconcini, R. Pacciani, A. Arnone, *Harmonic balance Navier-Stokes analysis of tidal stream turbine wave loads, Recent Advances in CFD for Wind and Tidal Offshore Turbines*, Springer Tracts in Mechanical Engineering, E. Ferrer and A. Montlaur editors, Springer International Publishing, 2019.

4. J. Drofelnik, A. Da Ronch, M.S. Campobasso, *Harmonic balance Navier-Stokes aerodynamic analysis of horizontal axis wind turbines in yawed wind*, Wind Energy, **21**(7), 2018, pp. 515-530.

5. M.S. Campobasso, J. Drofelnik, F. Gigante, *Comparative Assessment of the Harmonic Balance Navier-Stokes Technology for Horizontal and Vertical Axis Wind Turbine Aerodynamics*, Comput. Fluids, **136**, 2016, pp. 354-370.

Harmonic balance ARCTIC/COSA solvers

- For given N_h and ω, express sought periodic solution as

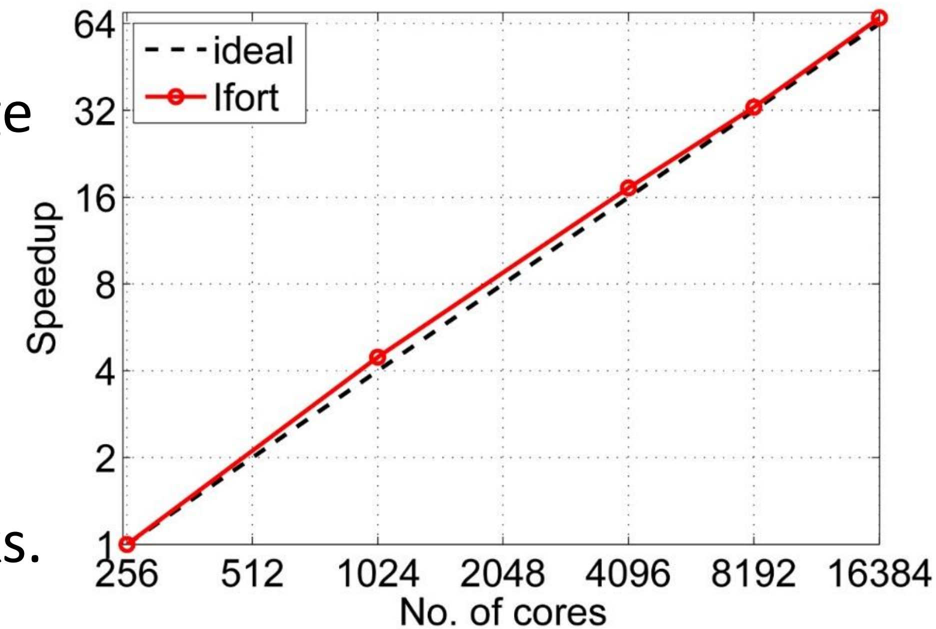
$$\mathbf{U}(t) = \hat{\mathbf{U}}_o + \sum_{n=1}^{N_H} (\hat{\mathbf{U}}_{2n-1} \cos(\omega n t) + \hat{\mathbf{U}}_{2n} \sin(\omega n t))$$

FEATURES

- Reduces analysis of time-periodic flows by 30 to 50 times over conventional time-domain method due to:
  - Treating unsteady problem as steady: no physical transient.
  - Enabling use of multi-frequency periodicity BCs
- Captures flow nonlinearity quite well.
- RAM memory increases by factor ($2N_h$+1), but explicit CFD is not RAM-demanding

Parallelization

- High parallel efficiency of computing section, enabling large simulations to be run in a few hours.
- Strong scalability test:
  - HB4 plunging wing analysis.
  - 67,108,864-cell 16,384-blocks.

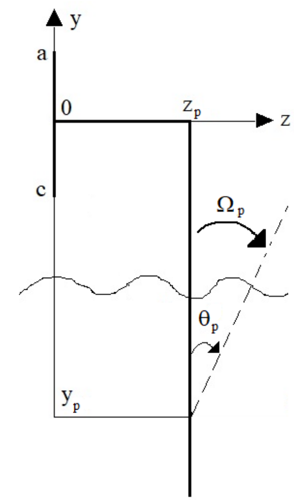


- Efficient parallel handling of all large I/O files[6].
  - Supports CGNS and TECPLOT, enabling interfacing with common grid generation and post-processing software

6. A. Jackson, M.S. Campobasso, J. Drofelnik, *Load balance and parallel I/O: optimising COSA for large simulation*, Computers and Fluids, Vol. 173, 2018, pp. 206-215.

Kinematics of FOWT rotor grids

Tower angular position: $\theta_{tp} = \Theta_{tp} \sin\left(\Omega_{tp} t + \phi_{tp}\right)$



Grid displacements:

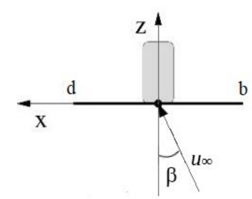
$$
\begin{aligned}
x_{tp} &= x_{rt} \\
y_{tp} &= y_{rt} - (z_{rt} - z_{pc}) s_{tp} + (y_{rt} - y_{pc})(c_{tp} - 1) \\
z_{tp} &= z_{rt} + (z_{rt} - z_{pc})(c_{tp} - 1) + (y_{rt} - y_{pc}) s_{tp}
\end{aligned}
$$

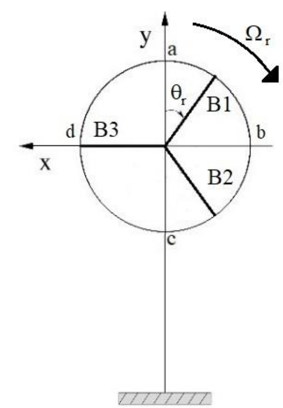
where:

$$
\begin{aligned}
c_{tp} &= \cos\theta_{tp} \\
s_{tp} &= \sin\theta_{tp}
\end{aligned}
\qquad \theta_r = \Omega_r t \qquad
\begin{aligned}
c_r &= \cos\theta_r \\
s_r &= \sin\theta_r
\end{aligned}
\qquad
\begin{aligned}
x_{rt} &= x_0 c_r - y_0 s_r \\
y_{rt} &= x_0 s_r + y_0 c_r
\end{aligned}
$$

Grid velocities:

$$
\begin{aligned}
\dot{x}_{tp} &= \dot{x}_{rt} \\
\dot{y}_{tp} &= \dot{\theta}_{tp} \left[-(z_{rt} - z_{pc}) c_{tp} - (y_{rt} - y_{pc}) s_{tp} \right] + \dot{y}_{rt} c_{tp} \\
\dot{z}_{tp} &= \dot{\theta}_{tp} \left[-(z_{rt} - z_{pc}) s_{tp} + (y_{rt} - y_{pc}) c_{tp} \right] + \dot{y}_{rt} s_{tp}
\end{aligned}
$$





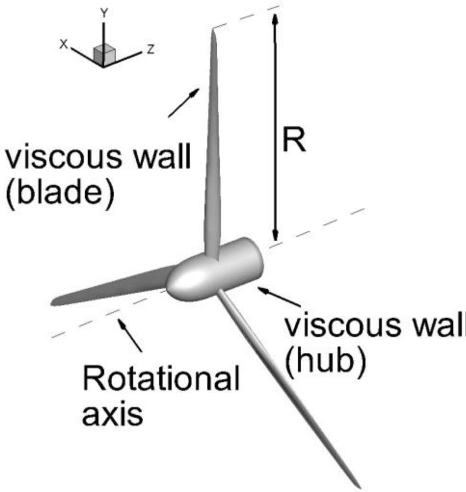
where:

$\dot{\theta}_{tp}$ $\quad \dot{\theta}_{tp} = \Theta_{tp} \Omega_{tp} \cos\left(\Omega_{tp} t + \phi_{tp}\right)$

$$
\begin{aligned}
\dot{x}_{rt} &= \left[-x_0 s_r - y_0 c_r \right] \Omega_r \\
\dot{y}_{rt} &= \left[x_0 c_r - y_0 s_r \right] \Omega_r
\end{aligned}
$$

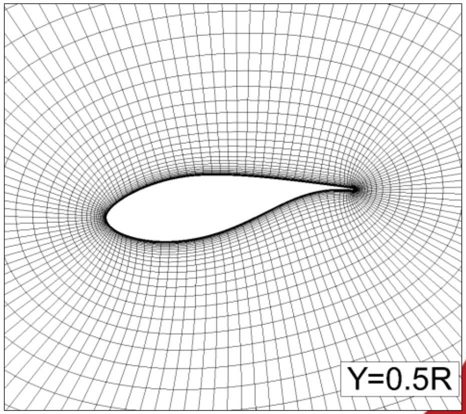
Results: NREL 5 MW turbine

- V_∞=11 m/s
- Ω_r: -12 RPM (0.2 Hz)
- Rotor tilt: 5°
- φ_{tp}=0°, β=0° and β=20°
- Θ_{tp}=1°; Ω_{tp}=0.1 Hz and Ω_{tp}=0.04 Hz
- y_{PC}=-90 m, z_{PC}=5 m



<u>Analysis codes</u>

- Time-domain and harmonic balance ARCTIC
- FLUENT
- NREL OpenFAST

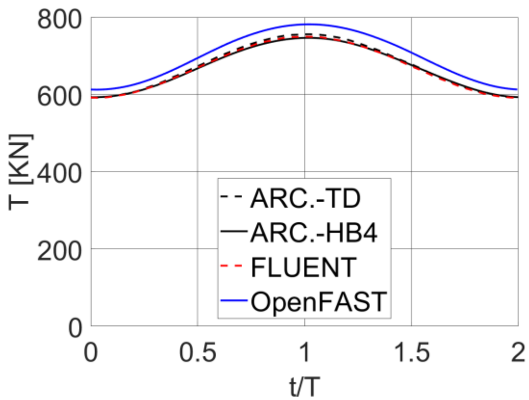


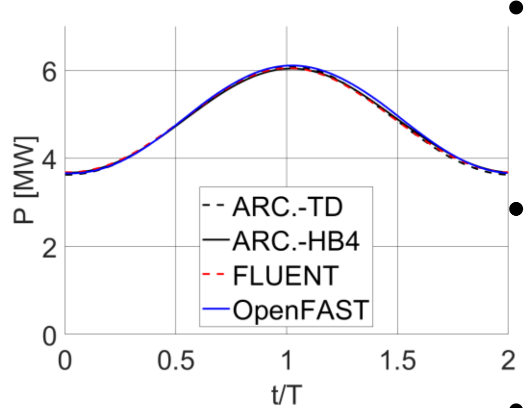
<u>CFD grid</u>

- FLUENT: about 10 M cells.
- ARCTIC: about 12 M cells.

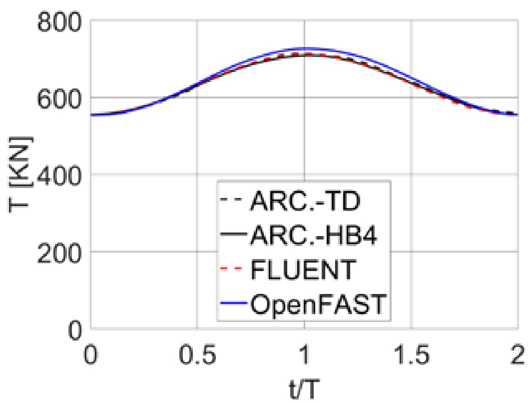
Results: rotor power and thrust at Ω_{tp}=0.1 Hz

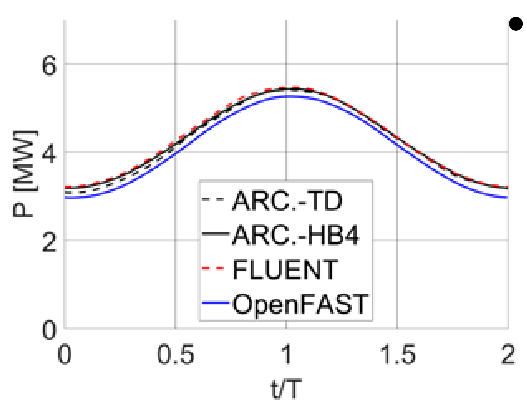
β=0°, Θ_{tp}=1°





β=20°, Θ_{tp}=1°

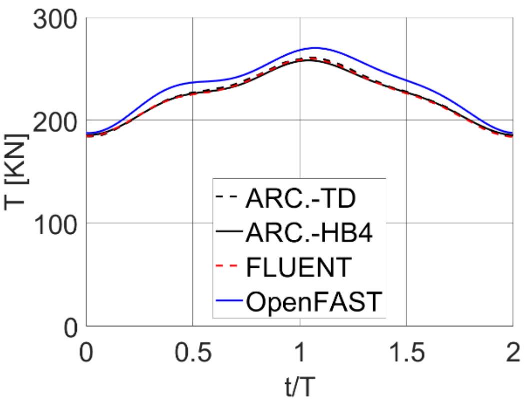


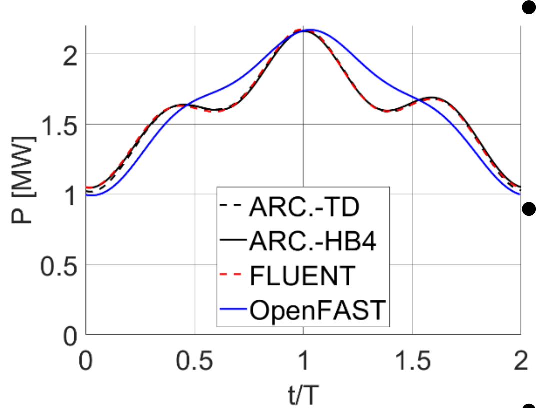


- All 3 CFD codes are in good reciprocal agreement
- At β=0° BEMT overpredicts peak CFD (HB4) T by 4.6%.
- At β=20° BEMT underpredicts peak CFD P by 3.4%.
- <u>4 harmonics are sufficient to capture flow nonlinearity</u>

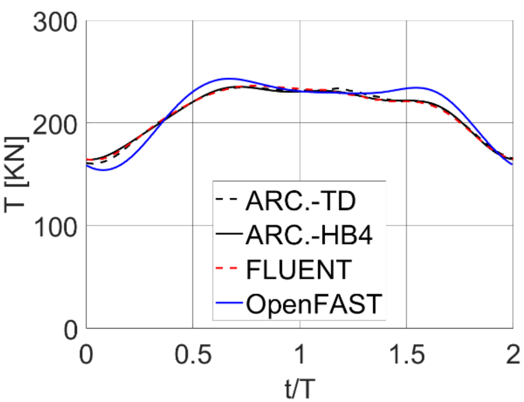
Results: blade power and thrust at Ω_{tp}=0.1 Hz

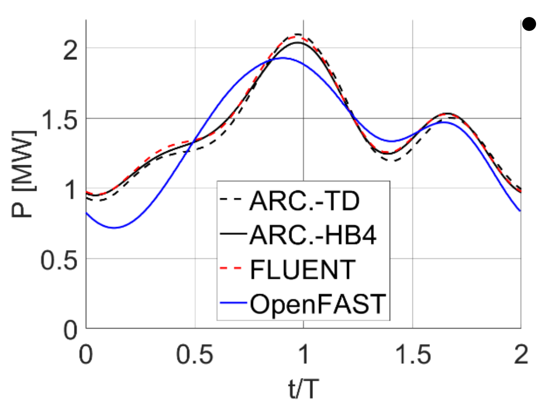
$\beta=0^o$, $\Theta_{tp}=1^o$





$\beta=20^o$, $\Theta_{tp}=1^o$

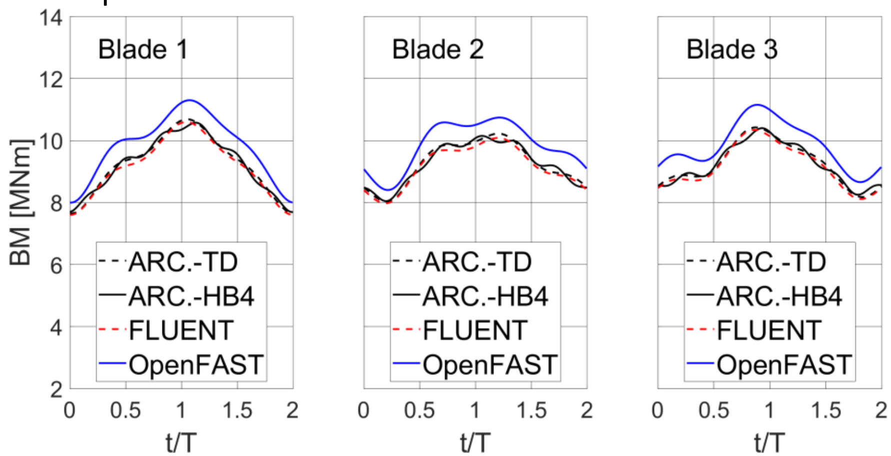




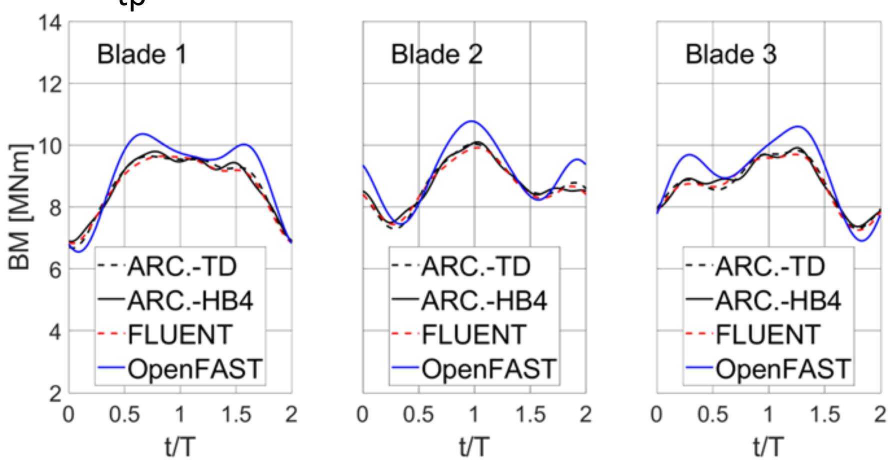
- All 3 CFD codes are in good reciprocal agreement
- At $\beta=0^o$ BEMT overpredicts peak CFD (HB4) T by 3.5%.
- At $\beta=20^o$ peak difference of BEMT and CFD P is 31.4%.
- 4 harmonics are sufficient to capture flow nonlinearity

Results: blade out-of-plane bending moment at Ω_{tp}=0.1 Hz

$\beta=0^o$, $\Theta_{tp}=1^o$



$\beta=20^o$, $\Theta_{tp}=1^o$



- All 3 CFD codes are in good reciprocal agreement
- At $\beta=0^o$ BEMT overpredicts peak CFD BM by 6.5%.
- At $\beta=20^o$ BEMT overpredicts peak CFD BM by up to 6.8%.
- 4 harmonics are sufficient to capture flow nonlinearity

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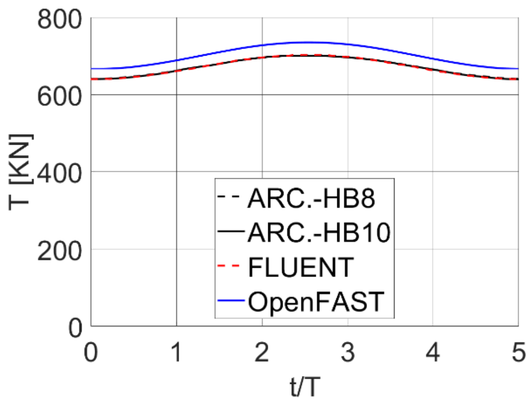
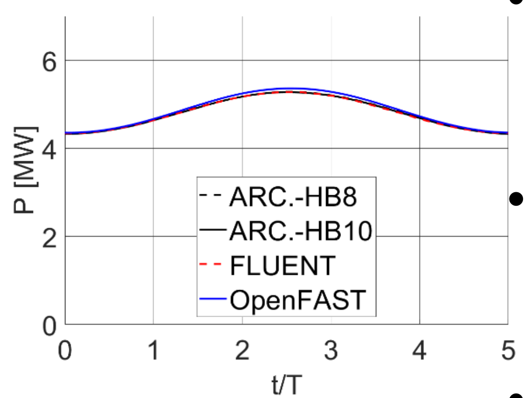
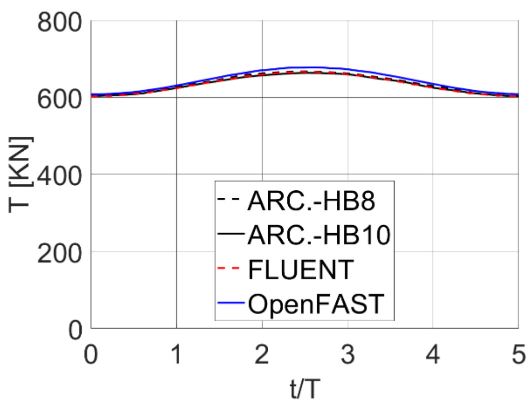
Results: rotor power and thrust at Ω_{tp}=0.04 Hz

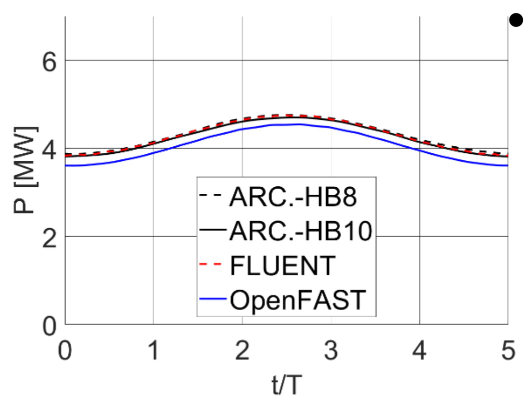
$\beta=0^o$, $\Theta_{tp}=1^o$





$\beta=20^o$, $\Theta_{tp}=1^o$





- All 3 CFD codes are in good reciprocal agreement
- At $\beta=0^o$ BEMT overpredicts peak CFD (HB4) T by 4.9%.
- At $\beta=20^o$ BEMT underpredicts peak CFD P by 3.4%.
- 8 harmonics are sufficient to capture flow nonlinearity

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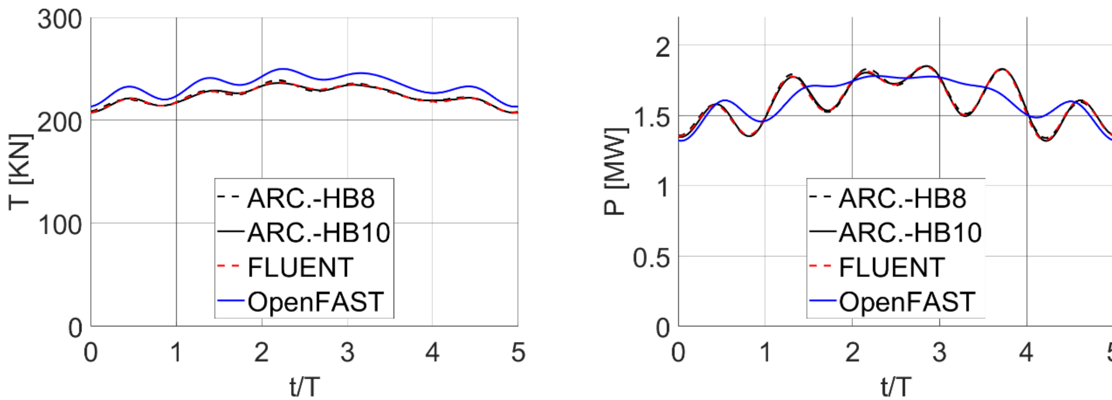
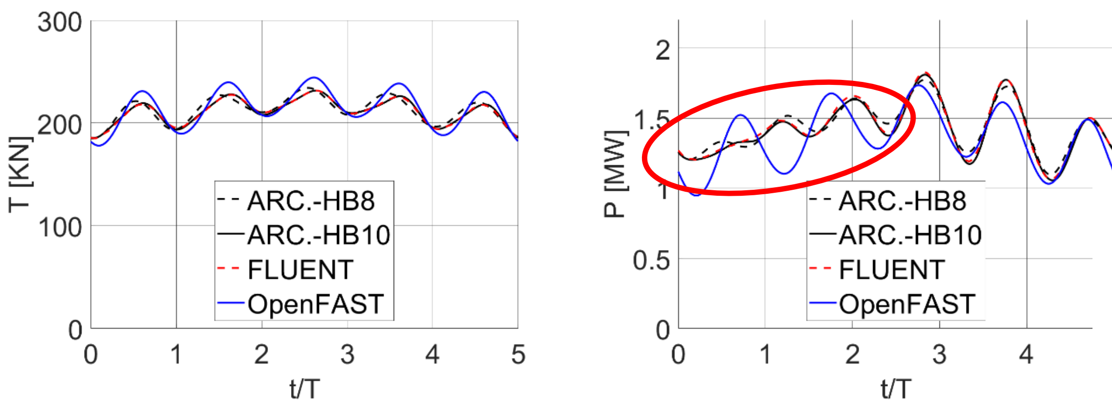
Results: blade power and thrust at Ω_{tp}=0.04 Hz

β=0°, Θ_{tp}=1°



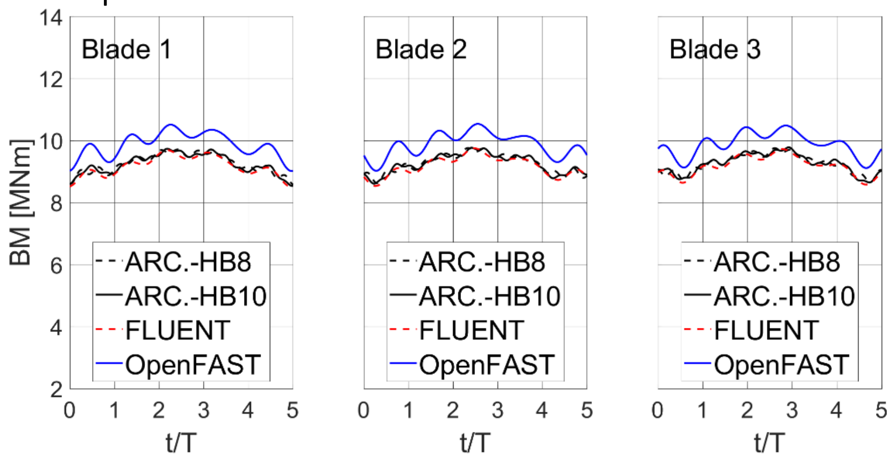
β=20°, Θ_{tp}=1°



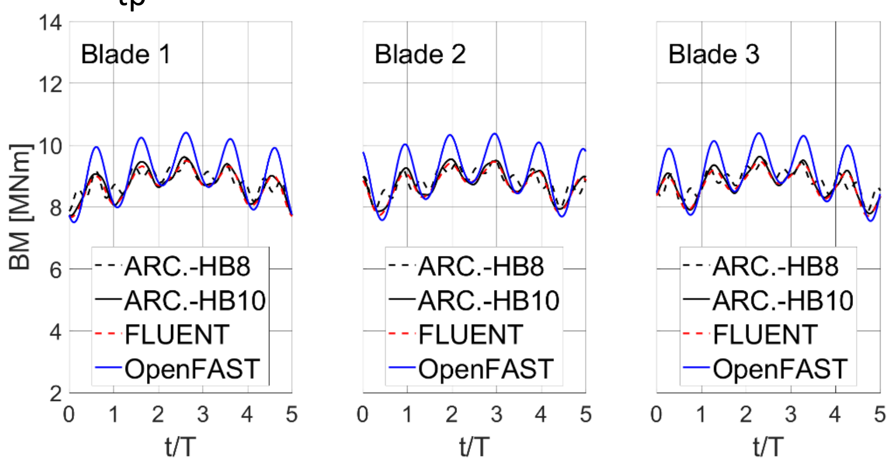
- All 3 CFD codes are in good reciprocal agreement
- At β=0° BEMT overpredicts peak CFD (HB4) T by 5.4%.
- At β=20° peak difference of BEMT and CFD P is 25.4%.
- 10 harmonics are sufficient to capture flow nonlinearity
- <u>BEMT blade P less oscillatory than CFD at β=0°; BEMT P & T more oscillatory at β=20°</u>

Results: blade out-of-plane bending moment at Ω_{tp}=0.04 Hz

β=0°, Θ_{tp}=1°



β=20°, Θ_{tp}=1°



- All 3 CFD codes are in good reciprocal agreement
- At β=0° BEMT overpredicts peak CFD BM by 7.8%.
- At β=20° BEMT overpredicts peak CFD BM by up to 9.6%.
- <u>To capture BM nonlinearity at β=20°, 10 harmonics are needed; FLUENT needs 6+ pitching cycles (30+ revs.).</u>

Summary

- Navier-Stokes CFD and BEMT predictions of pitching FOWT rotor aerodynamics performed at low and high Ω_{tp} with/without yaw error.
- Quantitative BEMT/CFD agreement at high Ω_{tp} is fair, with BEMT overpredicting rotor T by 4.6%, underpredicting rotor power by 3.4% and overpredicting peak BM by up to 7%.
- Quantitative BEMT/CFD agreement at low Ω_{tp} is TBC, with BEMT overpredicting T by 4.9%, underpredicting power by 3.4% and overpredicting peak BM by up to 9.6%.
- Largest qualitative differences are observed for misaligned wind, and agreement BEMT/CFD is worse at low Ω_{tp}.
- Harmonic balance CFD reduces by 2x to 4x cost of high-fidelity analysis, with benefit increasing as pitching frequency decreases.

COSA will be made opensource by end of 2023.

Thank you for your attention!

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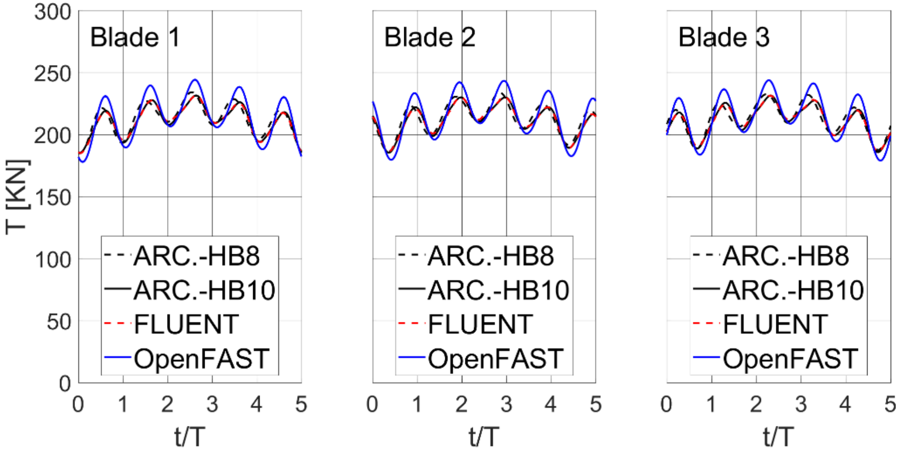
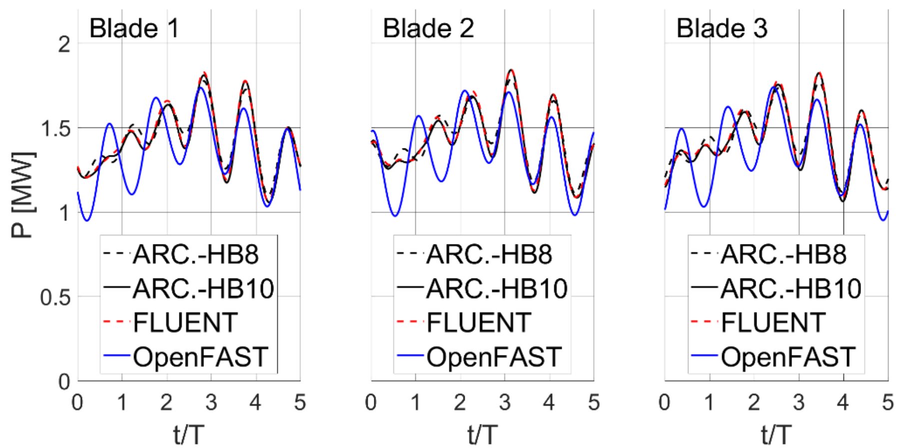
Any questions?

Results: blade power and thrust of all blades at Ω_{tp}=0.04 Hz

β=20°, Θ_{tp}=1°



β=20°, Θ_{tp}=1°



- All 3 CFD codes are in good reciprocal agreement