Determination of Added Mass Coefficients for Floating Hydrokinetic Turbine Blades using Computational Fluid Dynamics

Thanh Toan Tran, Will Wiley, and Hannah Ross
Water Power Foundation R&D Group, NREL

The CFD and post-processing approach successfully found added mass coefficients in 3 DOF. The coefficients were found to be highly dependent on the inflow and frequency, which only occur due to the viscous flow effects.

MOTIVATION AND OBJECTIVES

- Blade rotations and deflections under transient loading accelerate the surrounding water
  - ✓ ***Added mass*** force proportional to and in phase with the relative acceleration
  - ✓ Increased relevance for floating turbine systems / turbulent inflows
  - ✓ Contributes important physical effects for marine turbines – neglected by most mid-fidelity engineering turbine design tools
  - ✓ Blade section added mass forces have been added to OpenFAST's AeroDyn
    - Strip theory with user-defined 2D coefficients ($A_{tangential}$, A_{normal}, and A_{pitch})
    - Need an accurate definition of these coefficients
- Added mass is highly dependent on amplitude (Keulegan-Carpenter number) and frequency of motion
  - CFD is able to capture important viscous effects leading to these dependencies
- Reference axial-flow marine turbine, RM1, used for verification and repeatability

COMPUTATIONAL APPROACH

2D and 3D unsteady RANS solutions using STAR-CCM+ code
- K-ω SST turbulent model
- No free surface (2D) and free surface (3D)
- dt = oscillation period / 600

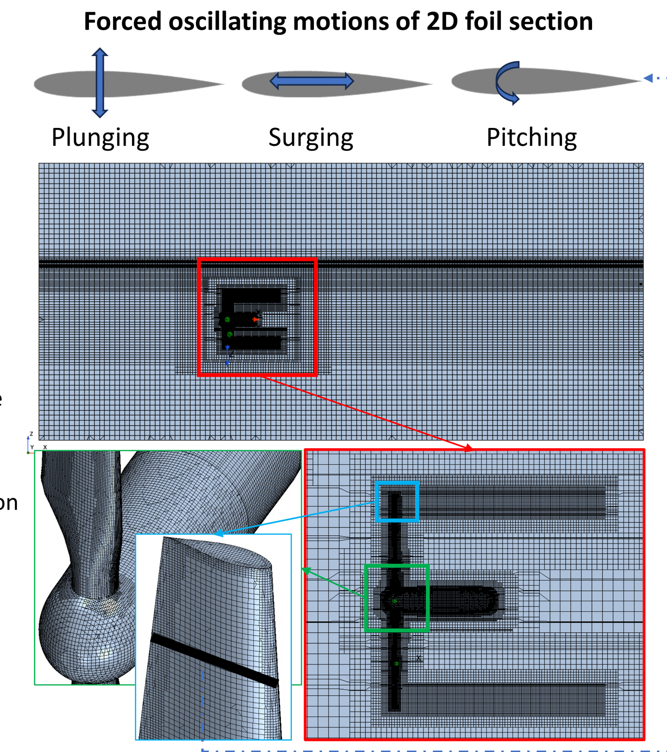
RM1 reference marine turbine

Inflow condition, V = 1.9 m/s

Rotating speed = 11.5 rpm

Forced oscillating condition:
- **2D CFD simulation:** Plunging, surging, and pitching airfoil motions of a given representative blade section (60% span) of the RM1 turbine with/without inflow conditions
  - ✓ Calm water and relative inflow velocity, Vr = 7.41 m/s
  - ✓ Plunging and surging amplitude = 1 m and a range of motion periods 6-12 seconds
  - ✓ Pitching motion amplitude = 5 deg and a range of motion periods 6-12 seconds
- **3D CFD simulation:** Surging motion at a base support structure from the floating quad RM1 turbine
  - ✓ Surge amplitude = 1m
  - ✓ Surge period = 6 s

Forced oscillating motions of 2D foil section



POST-PROCESSING

a. **Least square fitting model** - Fitting function
- $F_{N/T} = Fa_{N/T}\dot{v} + Fd_{N/T}v + Fhyd_{N/T}V_r^2$
- $M_p = Ma_p\dot{v} + Md_p v + Mhyd_p V_r^2$

where,

The $F_{N/T}$, $Fa_{N/T}$, $Fd_{N/T}$, and $Fhyd_{N/T}$ are the total hydrodynamic, added-mass, damping, and unsteady hydrodynamic forces in normal-to-chord and tangential-to-chord directions, respectively.

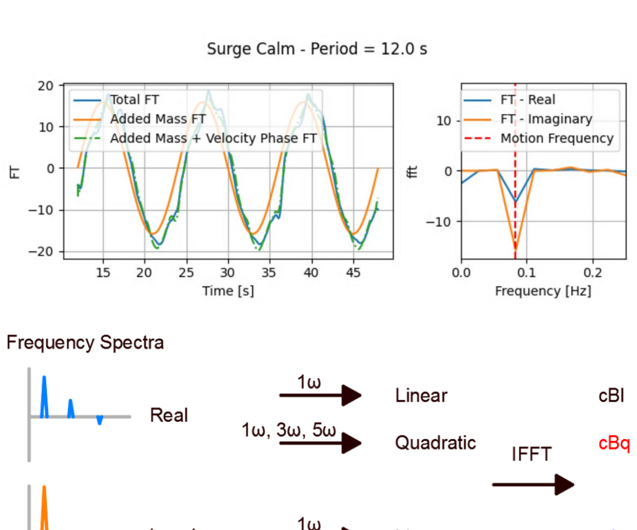
The M_p, Ma_p, Md_p, and $Mhyd_p$ are the total hydrodynamic, added-mass, damping, and unsteady hydrodynamic pitching moment, respectively.

The v, $\dot{v}$, and V_r are the oscillating velocity, oscillating acceleration, and relative inflow velocity, respectively.

The c and t are the chord length and thickness of airfoil at a given section.

$$Fa_{N/T} = Ca_{N/T}\frac{1}{2}\rho V\dot{v}$$
$$Fhyd = C_{N/T}\frac{1}{2}\rho S$$
$$M_p = Ca_p\rho V\frac{1}{12}(c^2 + t^2)$$

b. **Frequency domain**
- Real component is in phase with velocity
- Imaginary component is in phase with acceleration
- $Ca_t = \frac{F_{t\ im.}(f_{oscillation})}{\rho V}$
- $Ca_p = \frac{M_{p\ im.}(f_{oscillation})}{\rho V\frac{1}{12}(c^2+t^2)}$



RESULTS

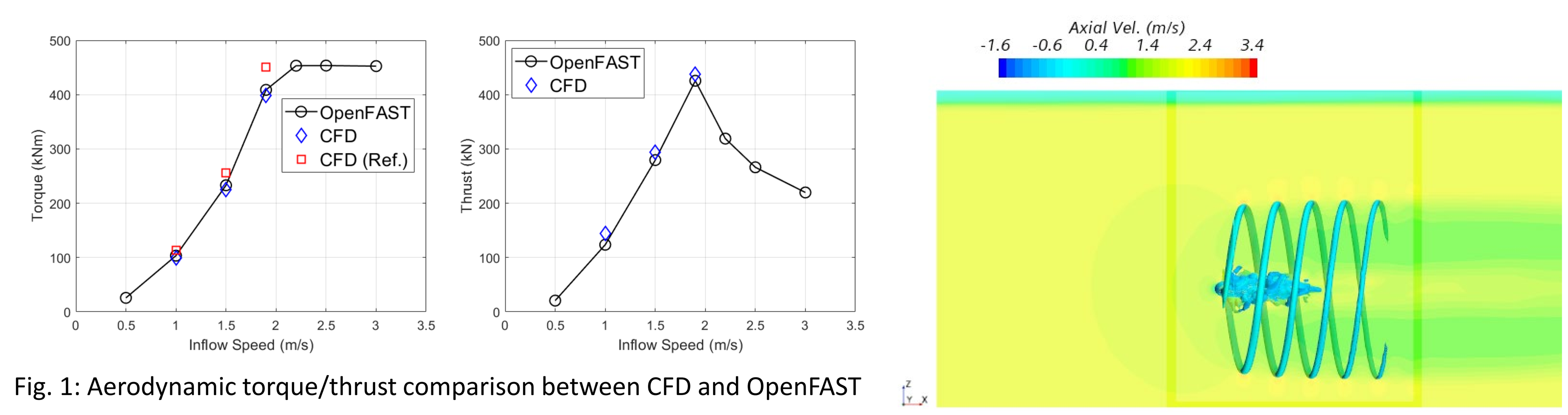


Fig. 1: Aerodynamic torque/thrust comparison between CFD and OpenFAST

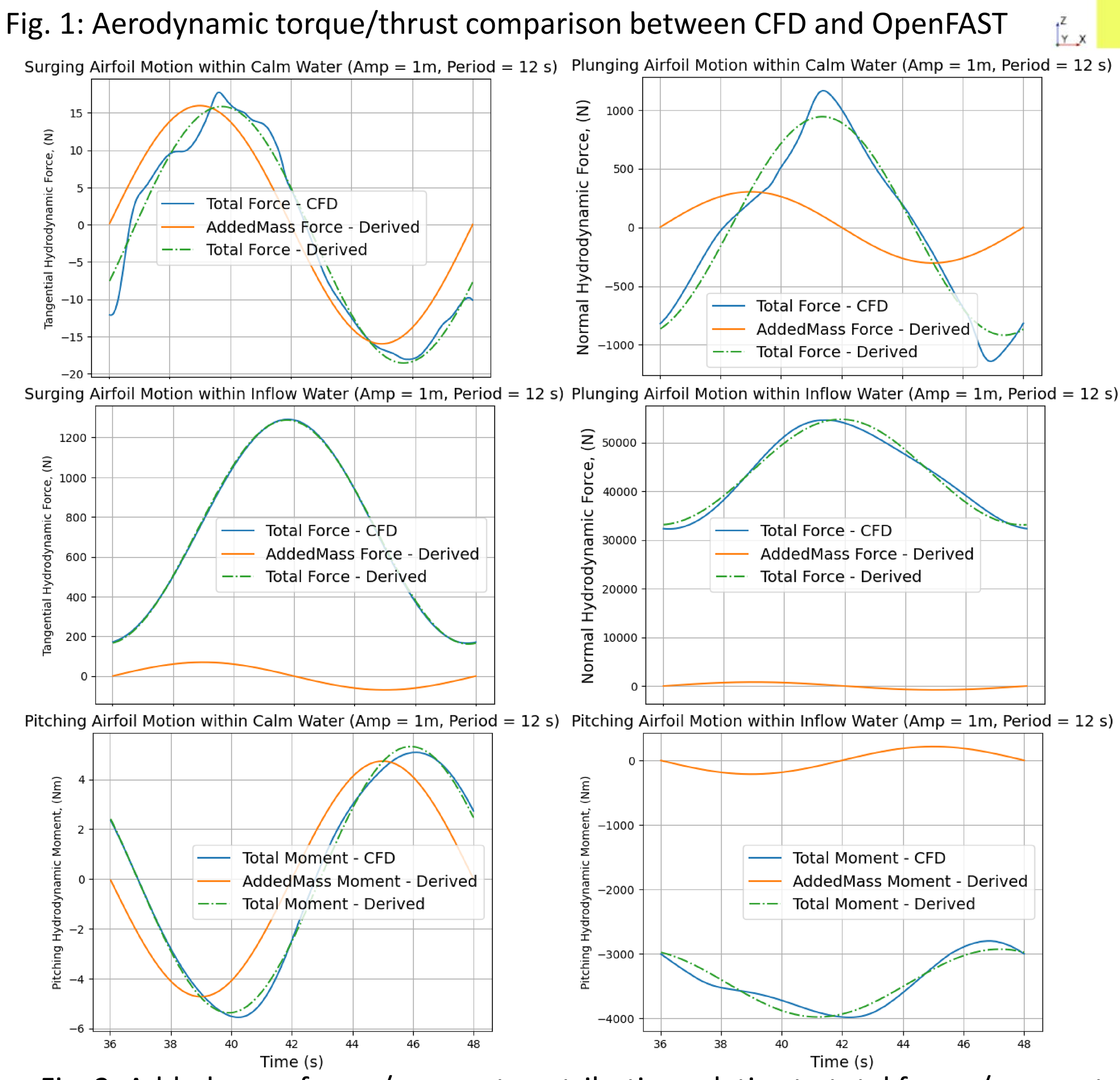


Fig. 2: Added-mass forces/moment contribution relative to total forces/moment using least-square fitting approach

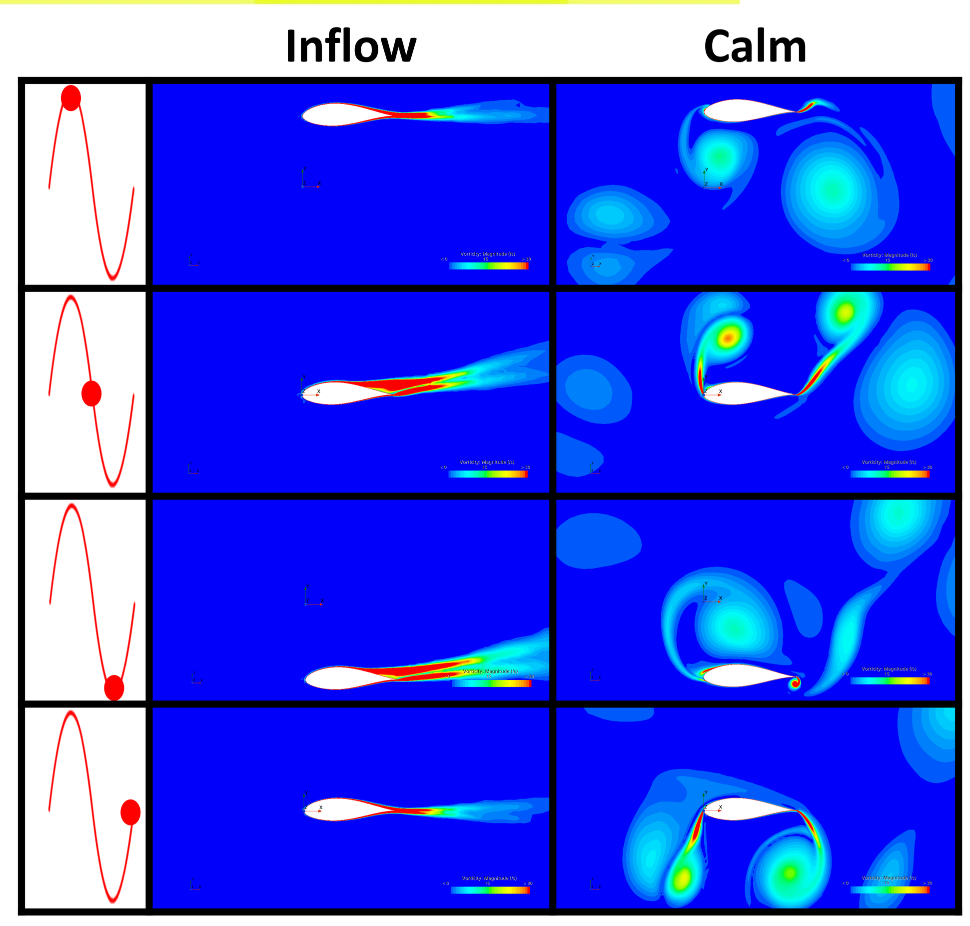


Fig. 3: Vorticity field throughout plunging oscillation

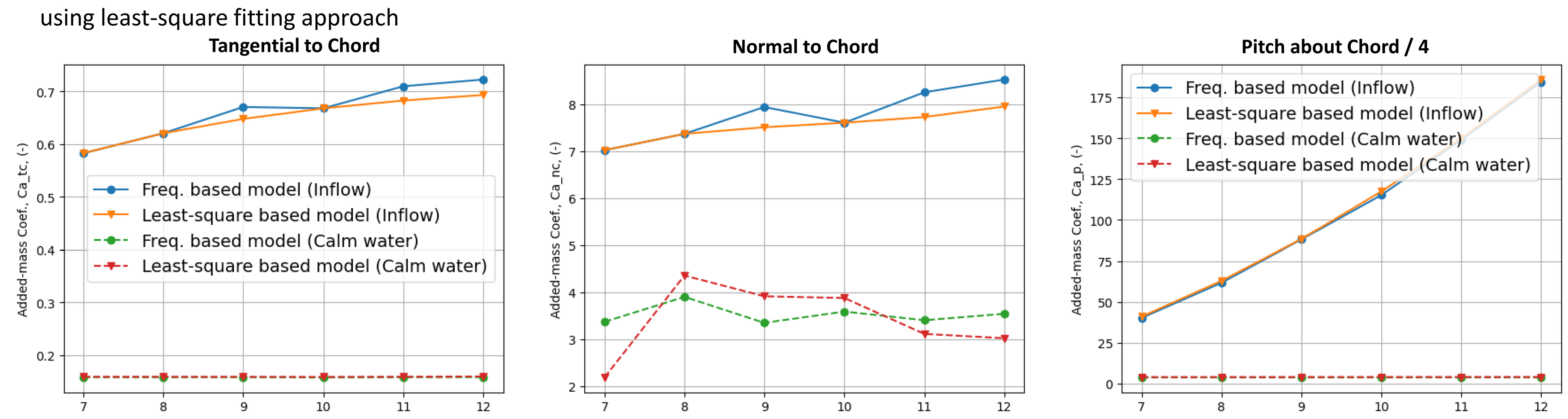


Fig. 4: Comparison of added-mass forces/moment coefficients calculated by different approaches

CONCLUSIONS

- Able to extract the added mass coefficients for translations and rotation of a foil section
  - Good agreement between least squares fitting approach and frequency domain approach
- Significant dependence on the mean flow condition (inflow vs. calm water)
  - Indicates there is also strong dependence on the amplitude of oscillation (Keulegan-Carpenter number)
- Dependence on frequency is much more significant when there is a mean inflow
- More 3D CFD simulation will be conducted to quantify added-mass coefficients at given blade sections

- Added-mass coefficient in normal-to-chord direction = 5.84
- Added-mass coefficient in chord-to-chord direction = 3.32

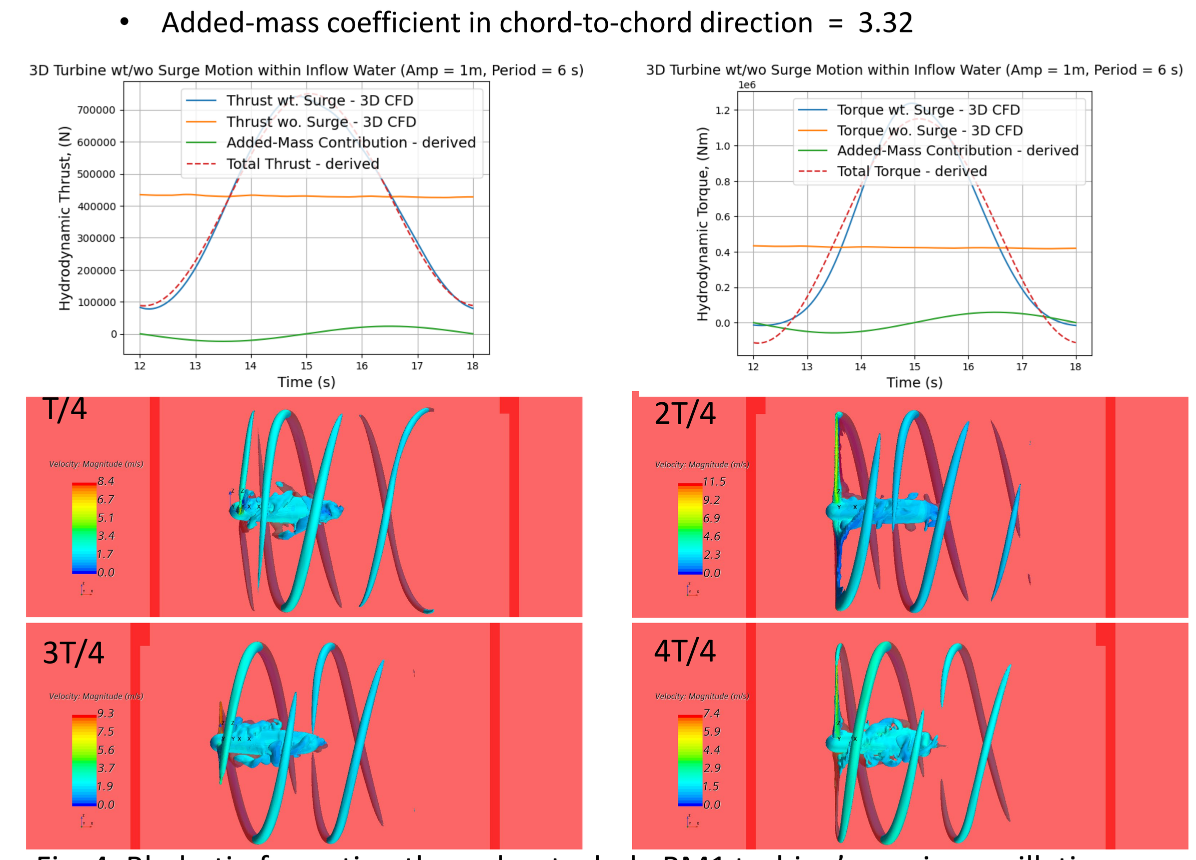


Fig. 4: Blade-tip formation throughout whole RM1 turbine's surging oscillation

CONTACT
Thanh Toan Tran
Water Power Foundational R&D Group
National Renewable Energy Lab.
ThanhToan.Tran@nrel.gov