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SAND2022-13908C

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A trade off study of metal and composite turbines using fluid-structure interaction modeling

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October 18, 2022

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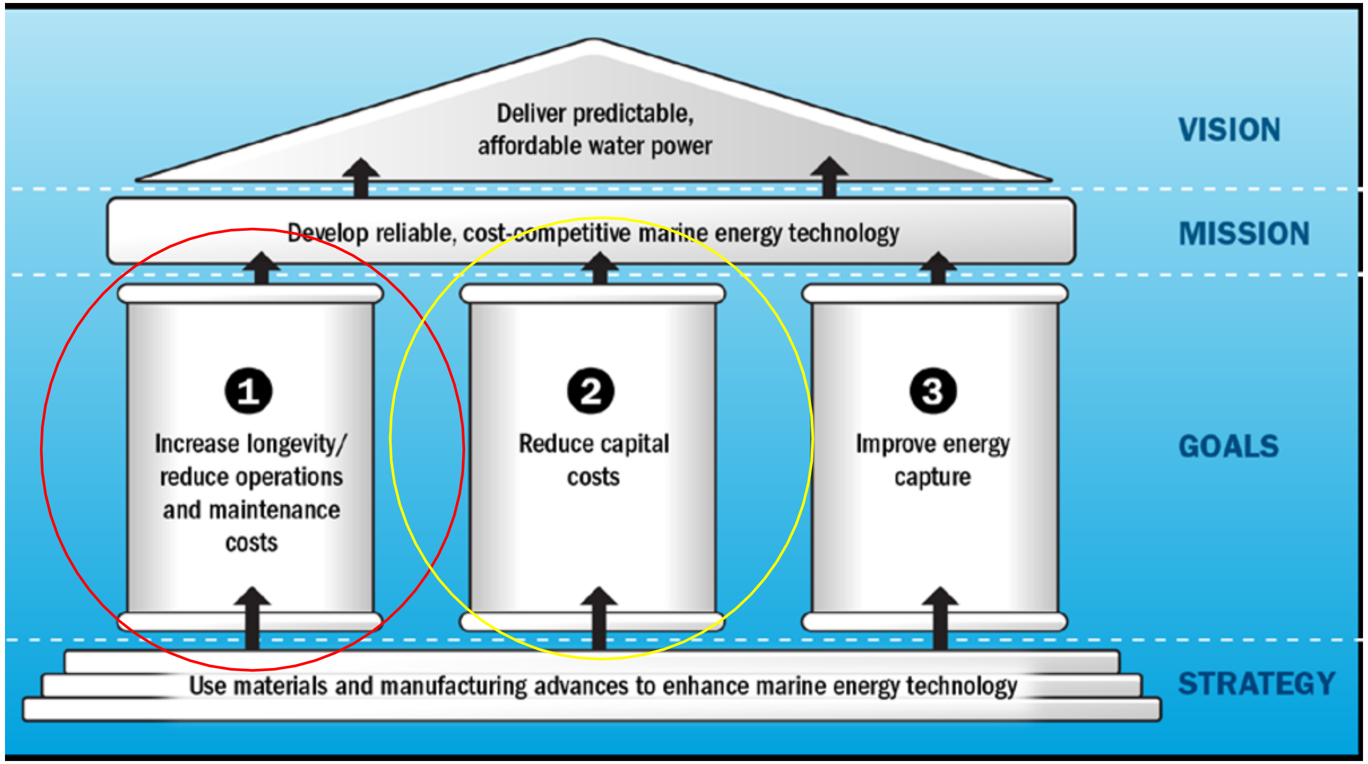
Motivation



WPTO's vision for materials and manufacturing in marine energy*

- The materials selected for marine energy devices must be able to perform under the harsh marine environment.
- WPTO draft Materials and Manufacturing Strategy^ identified FSI for non-rigid blades, as a near- and mid - term research needs.
- Current Energy Converter (CEC) design studies often *only* include Computational Fluid Dynamics (CFD) modeling with a simple rigid blade assumption or Finite Element Analysis (FEA) with simplified load distributions. This simplification can cause errors in predicting the device structural performance, reliability and LCOE.
- An FSI study takes into account the hydro-elastic behavior of the blade material, yield time-accurate solutions for loading and performance of a deforming rotor, which could be critical for understanding structural performance and failure modes.

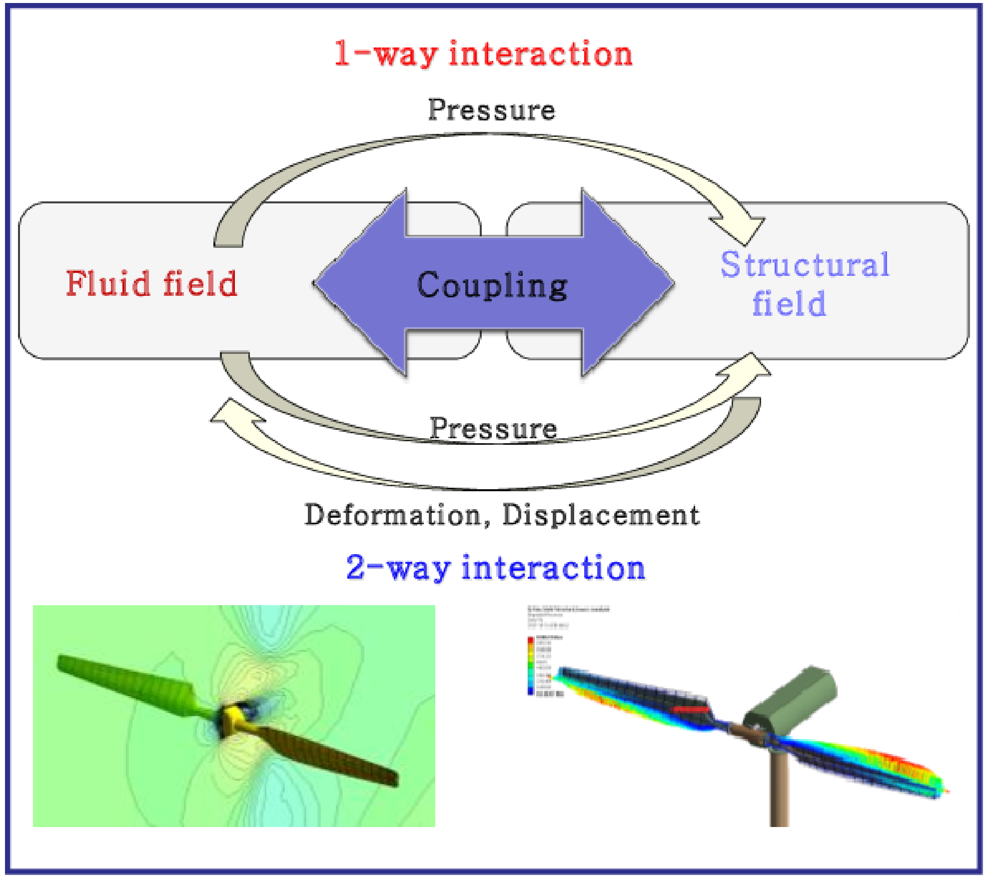
*DOE WPTO (2022) Summary Report: October 5, 2021 Workshop on Materials & Manufacturing for Marine Energy Technologies; May 2022
^DOE WPTO (draft) Materials and Manufacturing Strategy for Marine and Hydrokinetic Energy Technologies Research & Development

Objectives

Objectives: Perform FSI simulations for a reference tidal turbine (DOE Reference Model 1) made of metal and composites (e.g., FRP) and compare structural performance and cost

Structural performance metrics to observe include: deflection, stresses, ultimate limit state, fatigue limit state, vibration (flutter)

Project Plan (3 years):
2022: CFD model development, FSI simulations for metal blades (lab-scale)
2023: FSI simulations for composite blades (lab-scale) & metal blades (full-scale)
2024: FSI simulations for composite blades (full-scale) & final cost/LCOE calculations



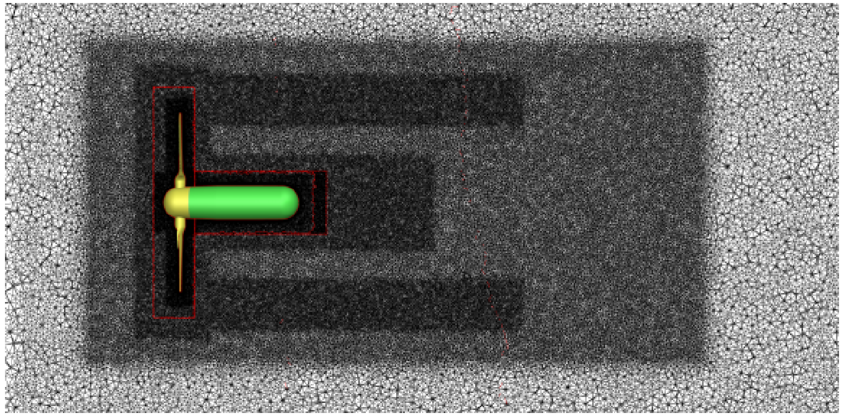
Fluid-structure interaction concept*

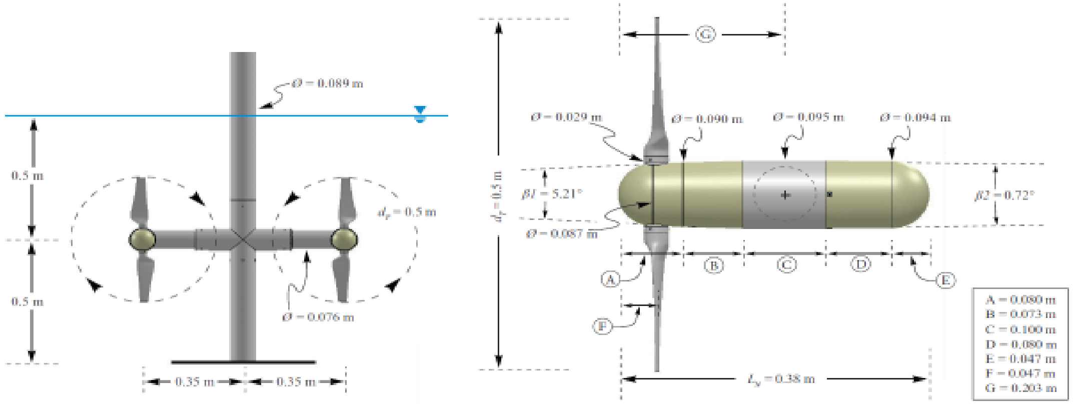
*Lee, Kyoungsoo & Huque, Ziaul & Kommalapati, Raghava & Han, Sangeul. (2015). The Evaluation of Aerodynamic Interaction of Wind Blade Using Fluid Structure Interaction Method. Journal of Clean Energy Technologies. 3. 270-275. 10.7763/JOCET.2015.V3.207.

CFD Setup

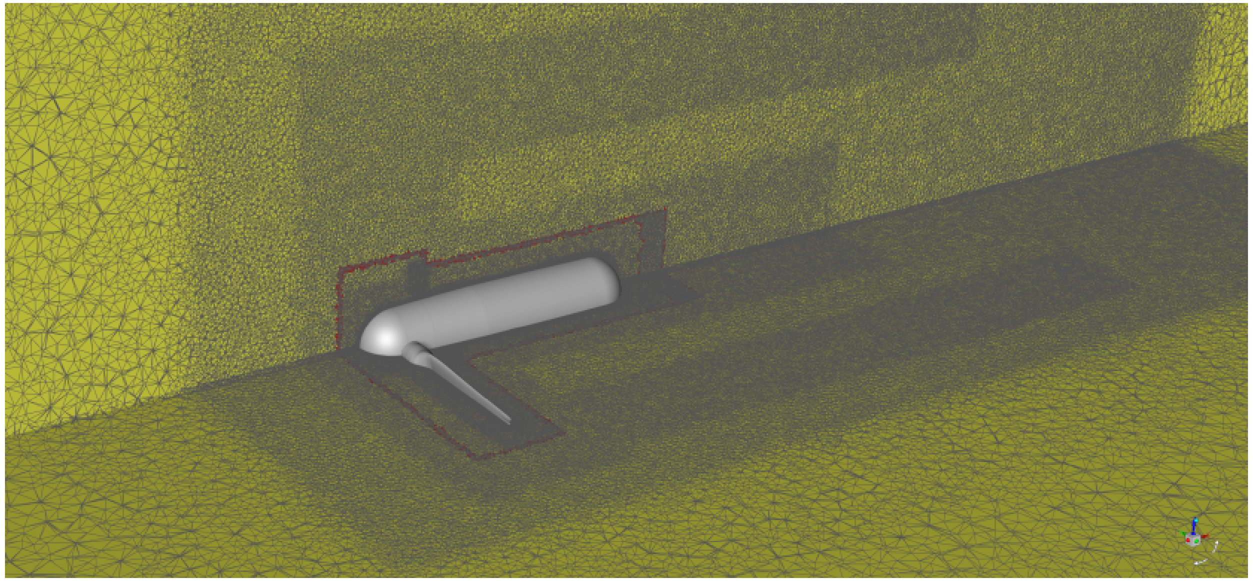
Computational Mesh (Medium grid)

- Tetrahedral mesh with overset multi-blocks, 29.4M cells
- No-slip wall: rotor, nacelle, bottom and right side
- Free surface effect is ignored (Slip wall)
- SST k-omega model
- $y^+ = 1.4$ on the rotor and nacelle wall
- Simulated on 128-516 cores (3-7 days)





1:40 scale RM1 turbine*



Computational Mesh for rotor and nacelle overset blocks and background domain

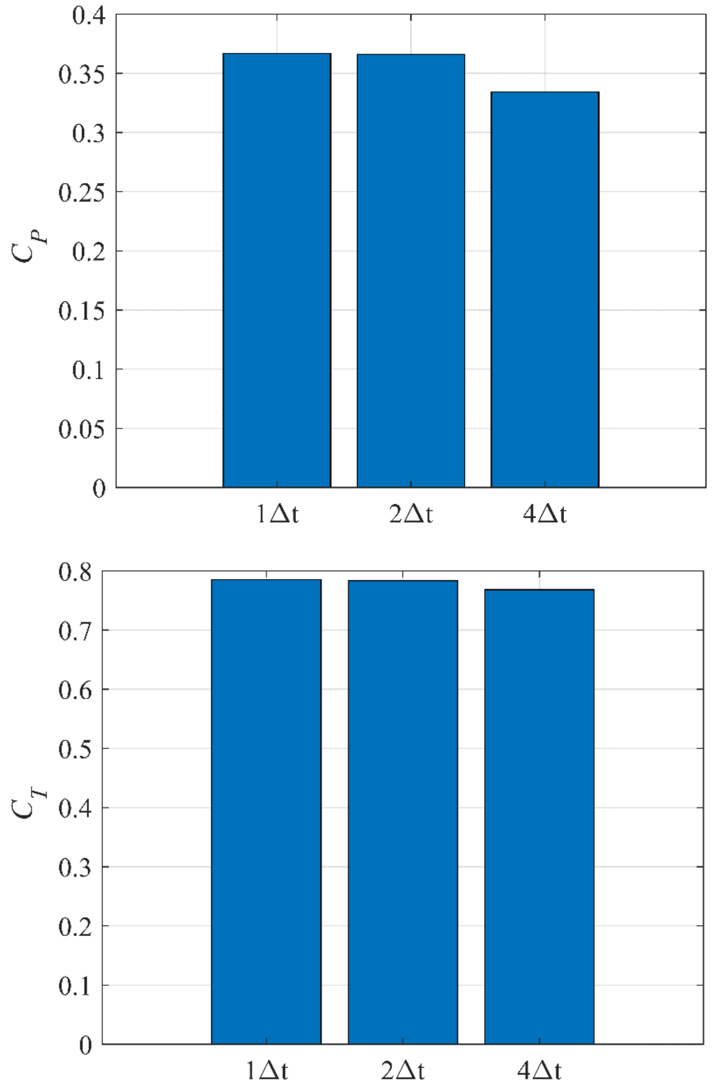
*Hill, C.; Neary, V.S.; Guala, M.; Sotiropoulos, F. Performance and Wake Characterization of a Model Hydrokinetic Turbine: The Reference Model 1 (RM1) Dual Rotor Tidal Energy Converter. *Energies* 2020

Temporal Convergence

Timestep size dependency (w/o blockage)

	Time step size	C_P (diff, %)	C_T (diff, %)
N_1	$1°$ rotation per Δt	0.3667 (-)	0.7850 (-)
N_2	$2°$ rotation per Δt	0.3660 (0.20)	0.7833 (0.22)
N_3	$4°$ rotation per Δt	0.3343 (8.86)	0.7681 (2.15)
U_{k_1}		0.008%	0.054%

U_{k_1} is uncertainty of N_1 obtained from the method of Stern et al. (2006); and Xing and Stern (2010)



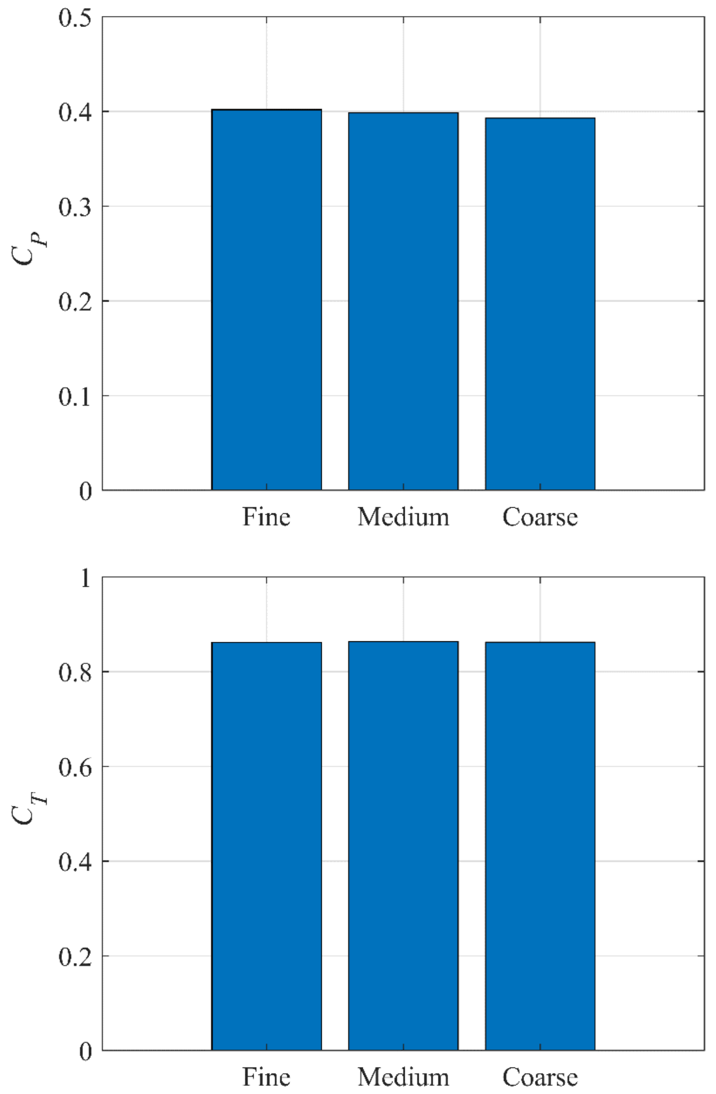
Estimated C_P and C_T depends on the time step size

Spatial Convergence

Mesh size dependency study (w/ blockage)

	# of cells	C_P (diff, %)	C_T (diff, %)
G_1	$66.2\ M\ (y^+ = 1)$	0.4018 (-)	0.8617 (-)
G_2	$29.4\ M\ (y^+ = 1.4)$	0.3984 (0.83)	0.8632 (0.18)
G_3	$14.5\ M\ (y^+ = 2)$	0.3928 (2.24)	0.8622 (0.06)
U_{k_1}		1.007%	-

U_{k_1} is uncertainty of G_1 obtained from the method of Stern et al. (2006); and Xing and Stern (2010)

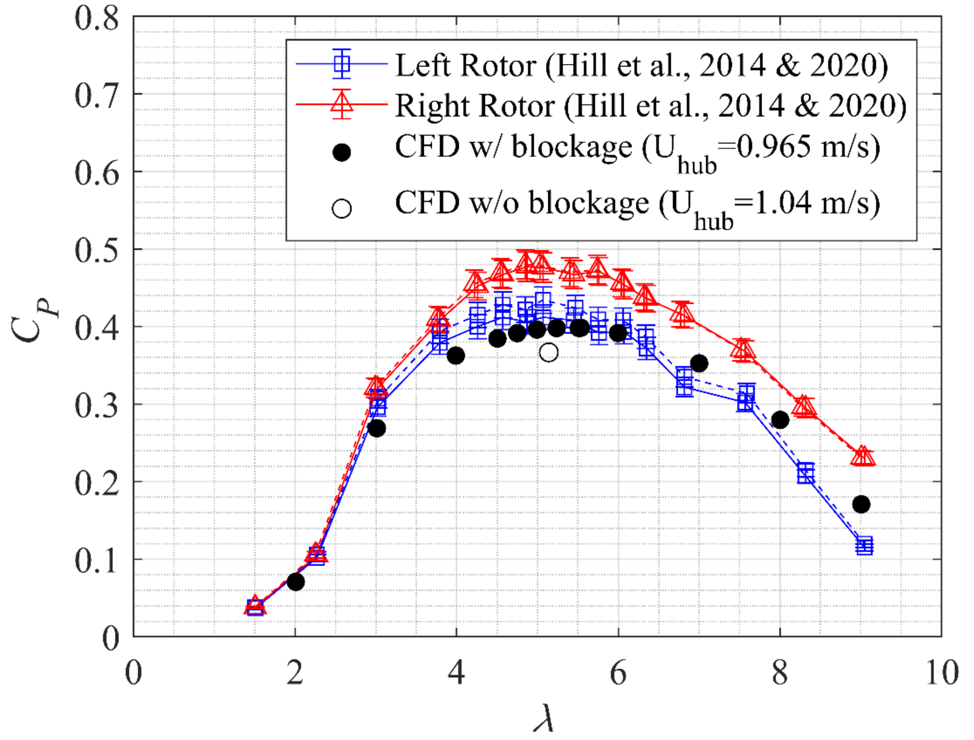


Estimated C_P and C_T depends on the mesh size

Turbine Performance

Coefficient of power

- Discrepancy between CFD w/o blockage and Exp. (Hill et al, 2014 & 2020) results due to the extensive blockage effect (14.3%)



Measured and estimated C_P vs. λ (coefficient of power vs. tip-speed ratio). Solid and dashed lines are from Hill et al, 2014 and 2020, respectively)

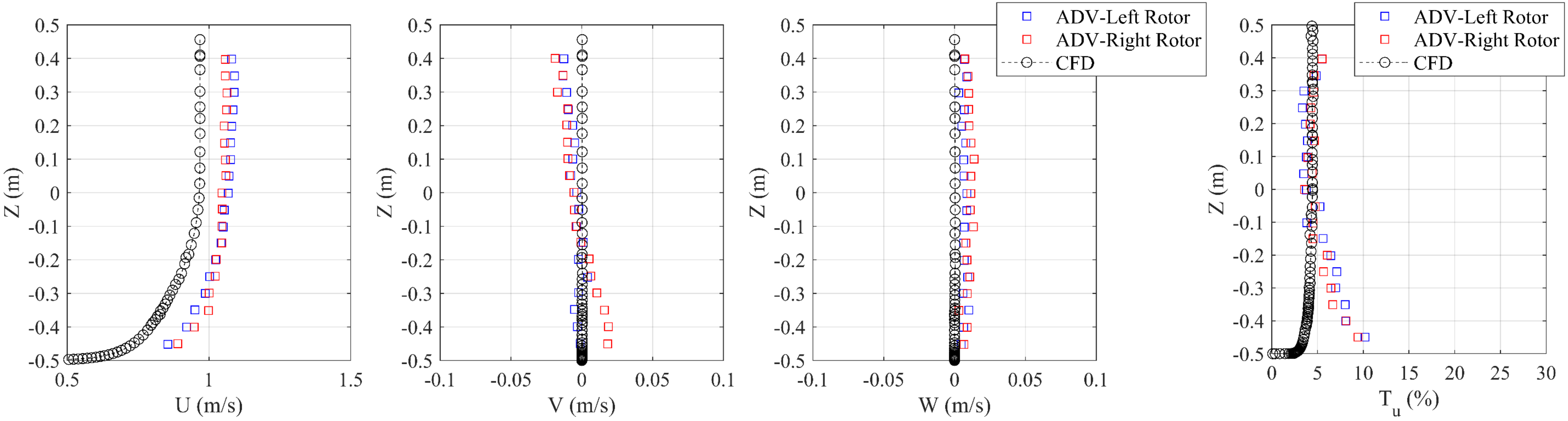
@ 204 rpm	C_P	Uncertainty
Exp. Left Rotor (TSR = 5.07)	0.412, 0.434	3.9 %
Exp. Right Rotor (TSR = 5.03)	0.476, 0.479	
CFD w/o blockage (TSR = 5.14)	0.367	
CFD w/ blockage (TSR = 5.54)	0.402	

Inflow Characteristics

Velocity and turbulence intensity profiles

- $U_{\text{hub,Exp}} \approx 1.04\, m/s \ @\ x = -3d_T$
- $U_{\text{hub,CFD}} \approx 0.965\, m/s \ @\ x = -3d_T$

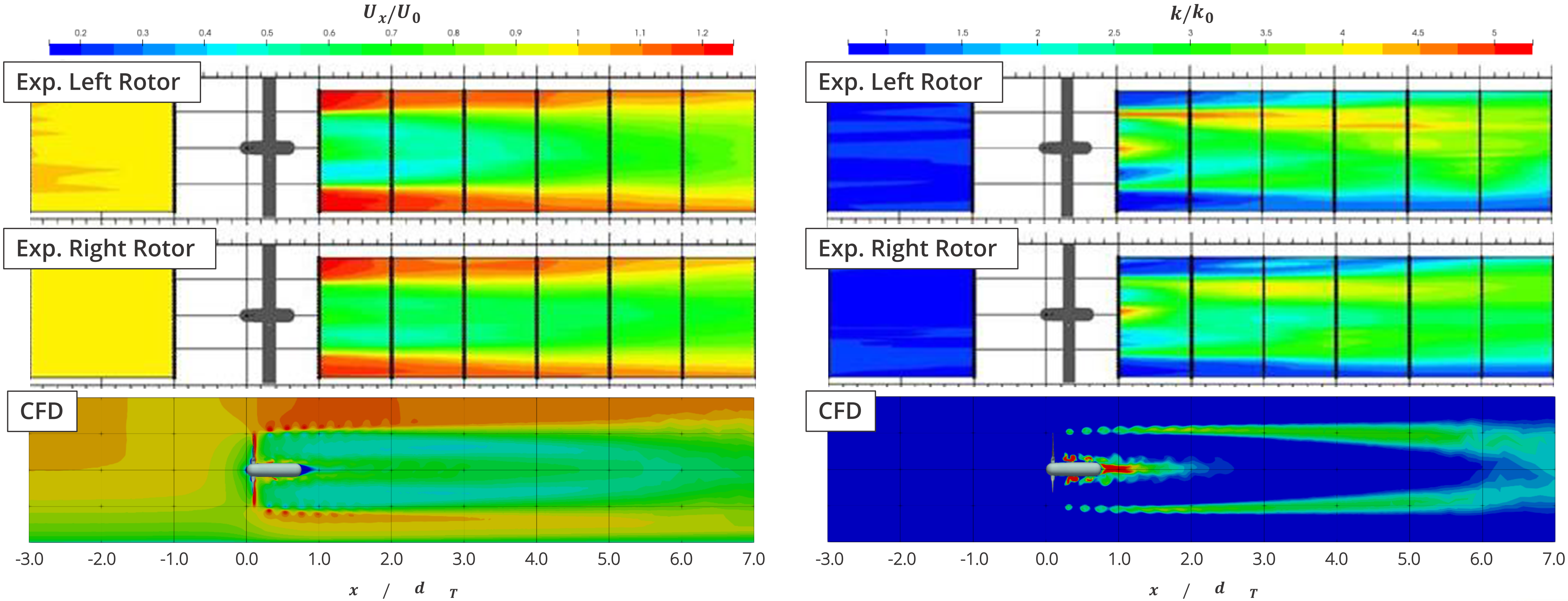
d_T: **Turbine diameter**
T_u: **Turbulence intensity**
ADV: Acoustic Doppler Velocimetry



Measured (red and blue square) and estimated (black circle) profiles for velocity components and turbulence intensity

Turbine Wake Characteristics

Normalized streamwise velocity and turbulent kinetic energy

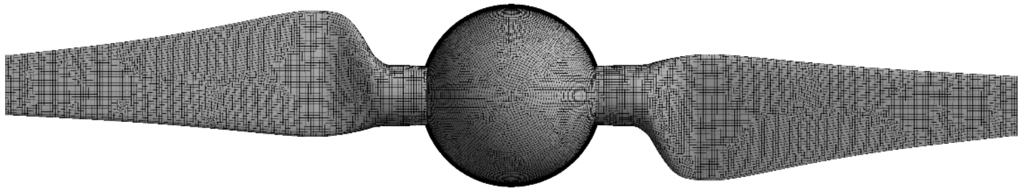


Measured (top) and estimated (bottom) normalized streamwise velocity (left column) and turbulent kinetic energy (right column) in x-z plane

FEA Model Setup

Geometry and mesh

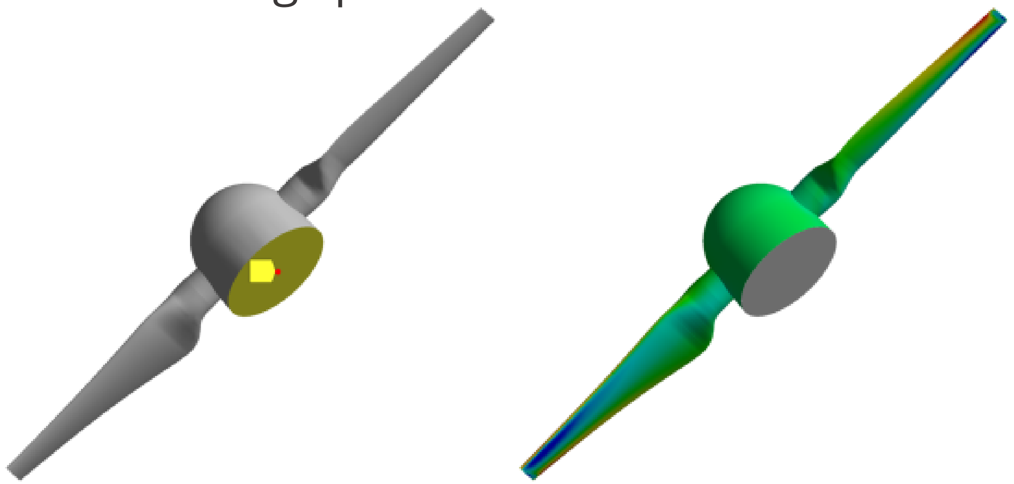
- Rotor only
- Hexahedral mesh with quadratic element order
- Modelled as a solid made from aluminum alloy



Generated mesh for FEA simulation (# of elements = 1.1M)

Boundary conditions

- Assigned angular velocity corresponding to the turbine rotating speed
- Displacement support at the turbine hub center
- A fluid-solid interface on the rotor surface

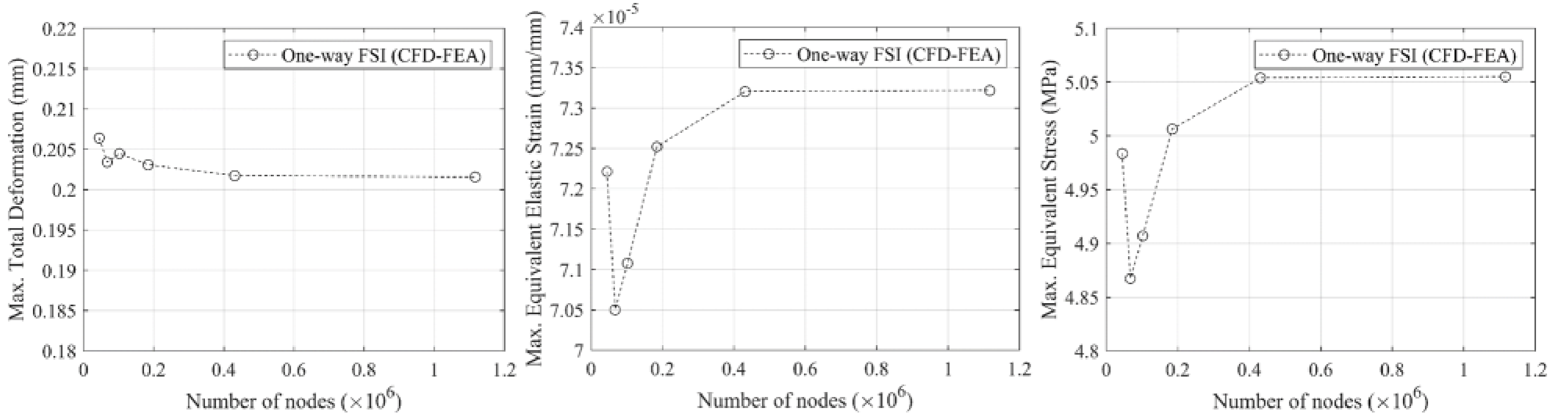


Remote displacement point (left) and pressure on the fluid-solid interface (right)

One-way FSI

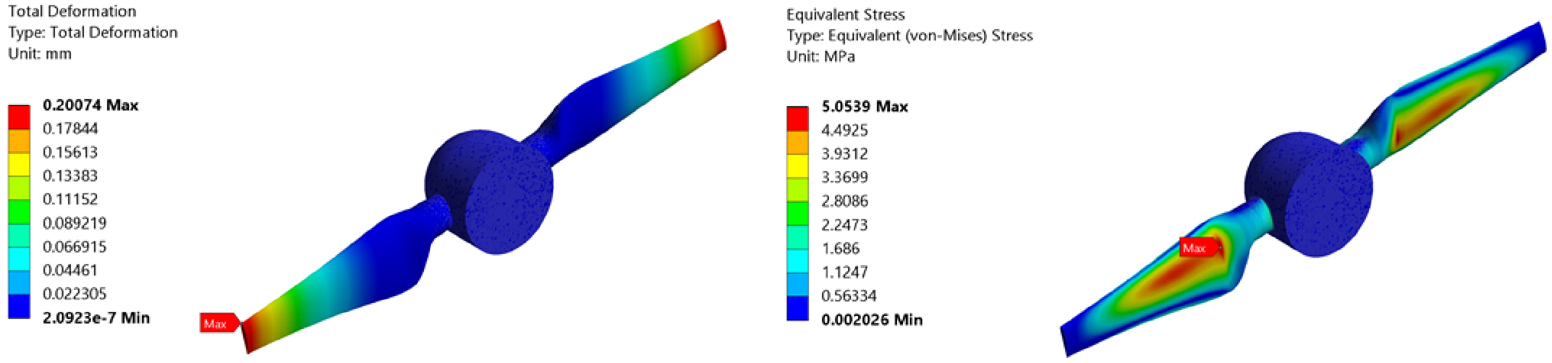
Simulation results at 204 rpm (TSR = 5.5)

- Mesh size dependency



Variation of estimated maximum deformation (left), strain (middle), and stress (right) with mesh density

- Estimated total deformation and equivalent stress



Max. total deformation = 0.2 mm

Max. equivalent stress = 5.05 MPa

Instantaneous contour plots of total deformation (left) and equivalent stress (right) on rotor

Next Steps

2022:

- CFD model development
- Structural model development
- 2-way FSI simulations, for metal blade~~s~~ model (lab-scale)
- Power performance & wake flow analyses
- Lots of learning:
  - Mesh optimization
  - CFD & Structural coupling
  - Challenges on running on different HPCs (Sandia's HPCs, ANSYS Cloud, etc.)

2023:

- FSI simulations for composite blades (lab-scale) & metal blades (full-scale)
- Power performance, hydrodynamic and structural hydroelastic analyses
- Preliminary cost/LCOE analysis

2024:

- FSI simulations for composite blades (full-scale)
- Final cost/LCOE calculations
- Final report/publications

THANK YOU

Questions? Comments?

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