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Comprehensive Verification and Validation of OpenFAST for Horizontal Axis Marine Hydrokinetic Turbine Modeling

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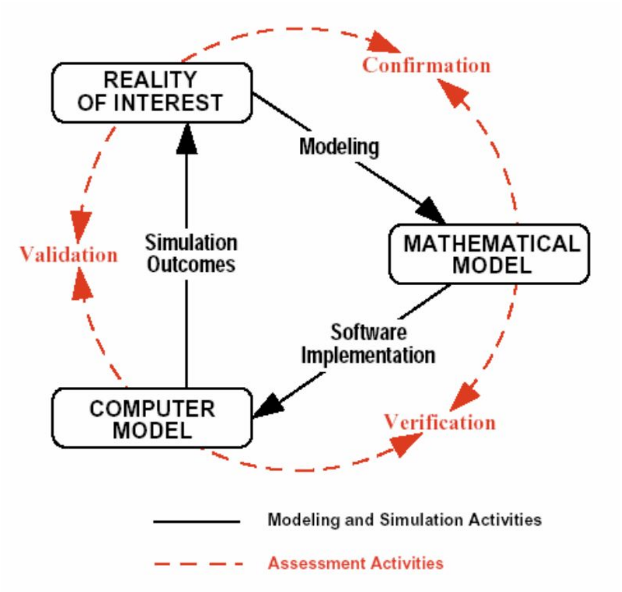
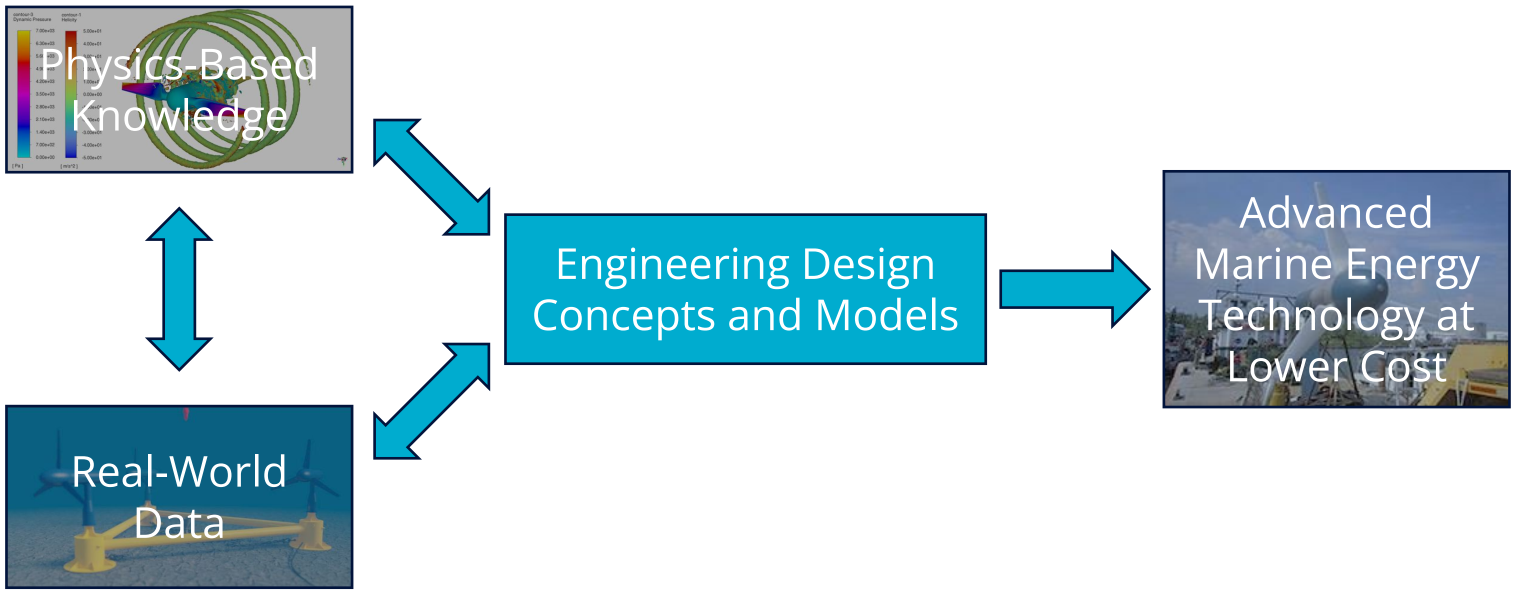
BACKGROUND

- Blade Element Momentum (BEM) and Free Vortex Wake (FVW) methods play a pivotal role in the design and analysis of wind and marine hydrokinetic turbine technologies.
- Model verification and validation (V&V) is important to assess accuracy and applicability.
- Verified and validated modeling tools that can predict turbine performance and loads are critical to de-risk deployments and accelerate industry success.



Simplified view of the model verification and validation process (Thacker et al. 2004)



- Thacker, Ben H., Scott W. Doebling, Francois M. Hemez, Mark C. Anderson, Jason E. Pepin, and Edward A. Rodriguez. "Concepts of model verification and validation." (2004).

OBJECTIVES

Verify and Validate OpenFAST Model

- AeroDyn: Both low-fidelity BEM and mid-fidelity free vortex wake (FVW) method (OLAF)
- Verify the model
  - Numerical errors
    - Temporal and spatial convergence studies
    - Parameterization sensitivity studies
- Validate the model to controlled environment scale rotor and turbine tests
  - Power performance (Cp, Ct, Cq vs. TSR)
  - Cavitation
  - Rotor inflow and wake
  - Blade loads, e.g., flapwise (FW), edgewise (EW), and torsion (pitch-moment)

VERIFICATION AND UNCERTAINTY ANALYSIS

Methodology (Roache 1998; Stern et al., 2001; Xing and Stern, 2010)

- Code verification via systematic convergence testing

$$\epsilon_{k21} = S_{k2} - S_{k1}$$

$$\epsilon_{k32} = S_{k3} - S_{k2}$$

$$R_k = \frac{\epsilon_{k21}}{\epsilon_{k32}}$$

If monotonically converged ($0 < R_k < 1$), then:

$$P_k = \frac{\ln\left(\frac{\epsilon_{k32}}{\epsilon_{k21}}\right)}{\ln(r_k)} \qquad P = \frac{P_k}{P_{kest}}$$

$$\delta^*_{REk1} = \frac{\epsilon_{k21}}{\left(r_k^{P_k} - 1\right)}$$

$$U_k = \begin{cases} (2.45 - 0.85P)|\delta^*_{REk1}| & \text{if} \quad 0 < P \le 1 \\ (16.4P - 14.8P)|\delta^*_{REk1}| & \text{if} \quad P > 1 \end{cases}$$

or

$$GCI = F_S \cdot |\delta^*_{REk1}|$$

$S_{k1,2,3}$: Solution from fine, medium coarse

R_k: Convergence ratio

r_k: Refinement ratio

P_k: Order of accuracy

P_{kest}: Theoretical order of accuracy

δ^*_{REk1}: Error from Richardson Extrapolation based on fine solution

U_k: Uncertainty based on the FS method

GCI: Grid convergence index based on the safety factor

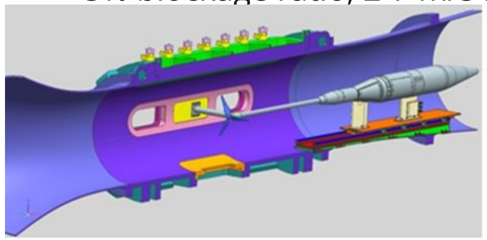
F_S: Safety factor, 1.25 for comparisons over three or more grids

- Roache, Patrick J. "Verification of codes and calculations." AIAA journal 36.5 (1998): 696-702.
- Stern, Fred, Robert V. Wilson, Hugh W. Coleman, and Eric G. Paterson. "Comprehensive approach to verification and validation of CFD simulations—part 1: methodology and procedures." J. Fluids Eng. 123.4 (2001): 793-802.
- Xing, Tao, and Frederick Stern. "Factors of safety for Richardson extrapolation." Fluids Eng. 132(6) (2010): 061403.

TURBINE ROTOR

Sandia-Applied Research Lab (SNL-ARL) MHKF1 Scale Reference Rotor Test Bed

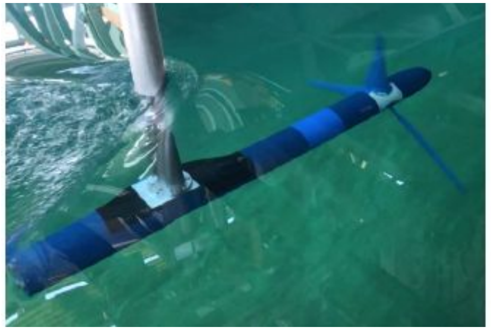
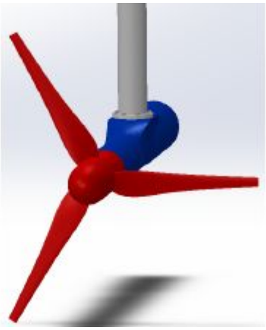
- Neary et al. 2013, Fontaine et al., 2020
- A 1:8.7 scale model of the 5.0-m diameter USDOE-MHKF1
- Three-bladed, D = 0.574m
- MHKF1 family hydrofoils
- Water tunnel test section D = 1.22m
- ~5% blockage ratio, 2-7 m/s inflow




- Performance, shaft loads, blade strain, flow field (LDV, PIV, SPIV), cavitation

Oxford Reference Tidal Turbine Benchmarking Project

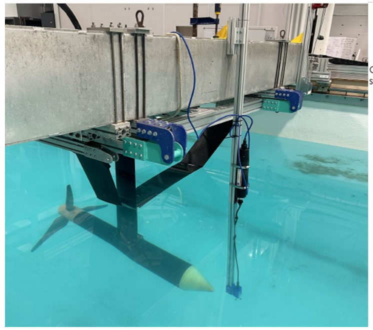
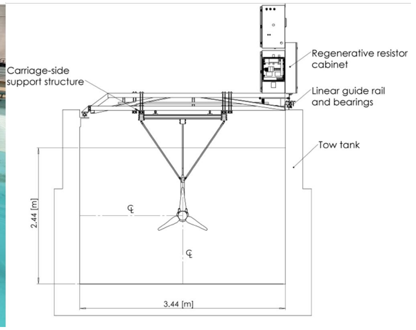
- Willden et al., 2023
- Large lab-scale 1.6-m diameter rotor
- Three blades using a constant hydrofoil section (NACA 63-415) along the span
- Large still water towing tank
- 3.05% blockage with low and elevated turbulence

- Performance, Flapwise and edgewise bending moments at multiple spanwise locations

Atlantic Marine Energy Center (AMEC) Reference Open-Source Tidal Energy Converter (OSTEC) (MHKF1) Scale Turbine Test Bed

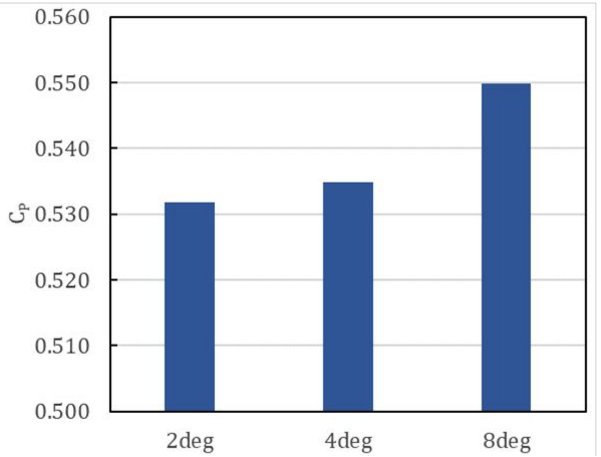
- Andersen, 2022
- A 1-m diameter scale model of OSTEC rotor
- MHKF1 family with thicker root sections for instrumentation
- UNH towing tank
- Blockage ratio of ~8.8%, 0.4 - 2.0 m/s towing speed

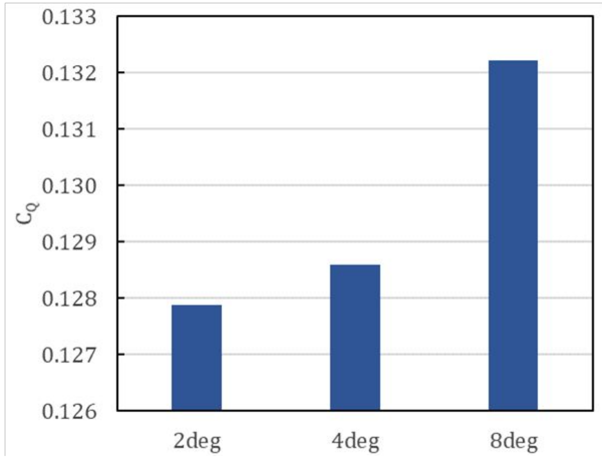



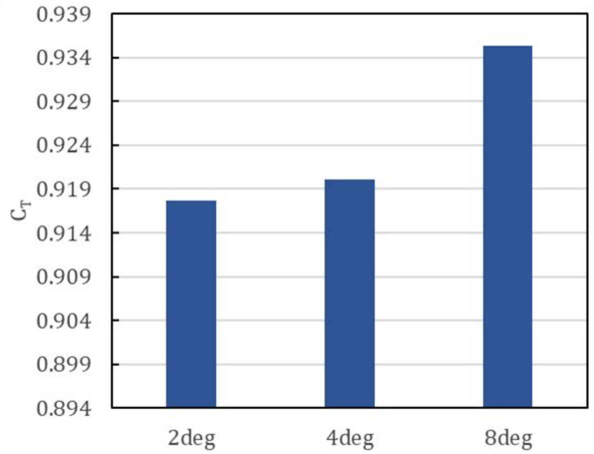
- Peformance, flapwise and lead-lag blade root bending moments

SNL-ARL MHKF1 - VERIFICATION AND UNCERTAINTY ANALYSIS

Time Step Size Dependency







1st order Euler method is used for solving the equation of motion for a vortex filament

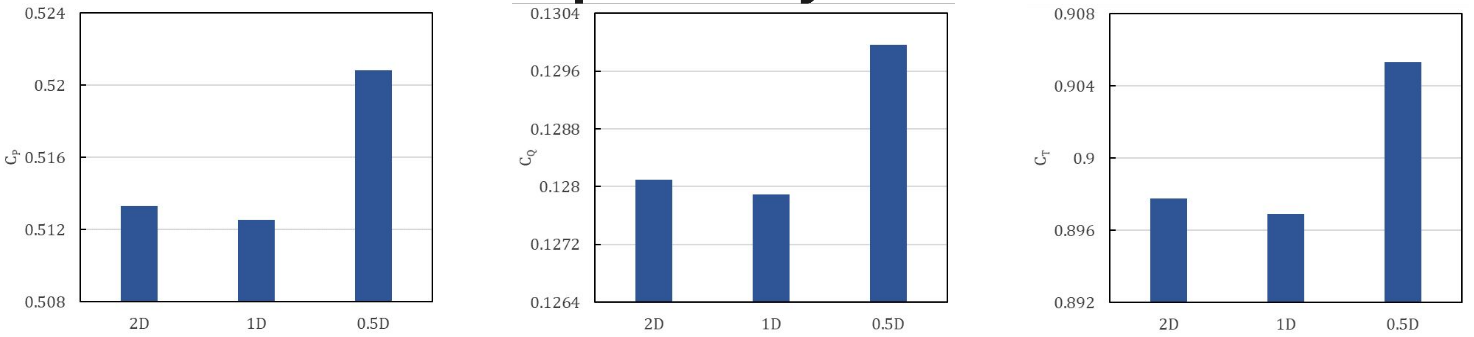
					Convergence							GCI
	2	0.0030	0.0151	0.2024	Monotonic Convergence	2.3050	1	2.3050	0.0008	0.28%	1.25	0.18%
	2	0.0007	0.0036	0.1996	Monotonic Convergence	2.3251	1	2.3251	0.0002	0.07%	1.25	0.18%
	2	0.0025	-0.0172	-0.1431	Oscillatory Convergence	2.8052	1	2.8052	0.0004	0.18%	1.25	0.06%

ϵ: Error between solutions
R_k: Convergence ratio
r_k: Refinement ratio
P_k: Order of accuracy
P_{kest}: Theoretical order of accuracy
δ: Error from Richardson Extrapolation
U_k: Uncertainty

Time step size corresponding to the **2 degrees rotation per each time step** is chosen for further V&V

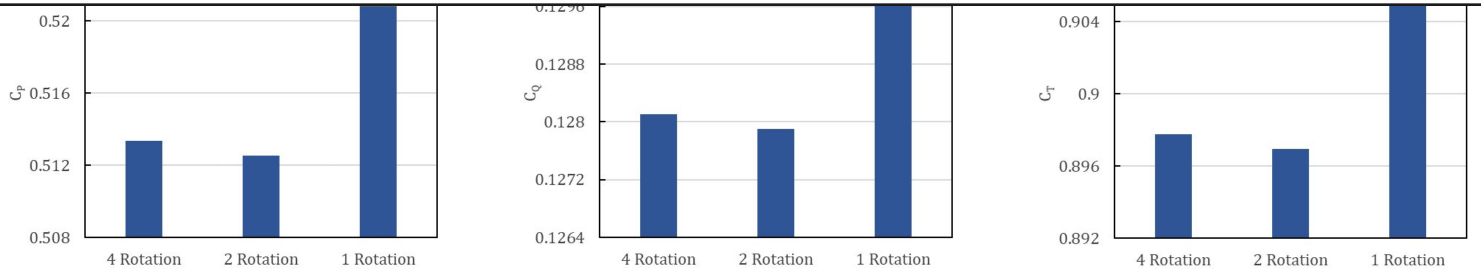
SNL-ARL MHKF1 - VERIFICATION AND UNCERTAINTY ANALYSIS

Number of Free Near Wake Panels Dependency



ϵ: Error between solutions
R_k: Convergence ratio
r_k: Refinement ratio
P_k: Order of accuracy
P_{kest}: Theoretical order of accuracy
δ: Error from Richardson Extrapolation
U_k: Uncertainty

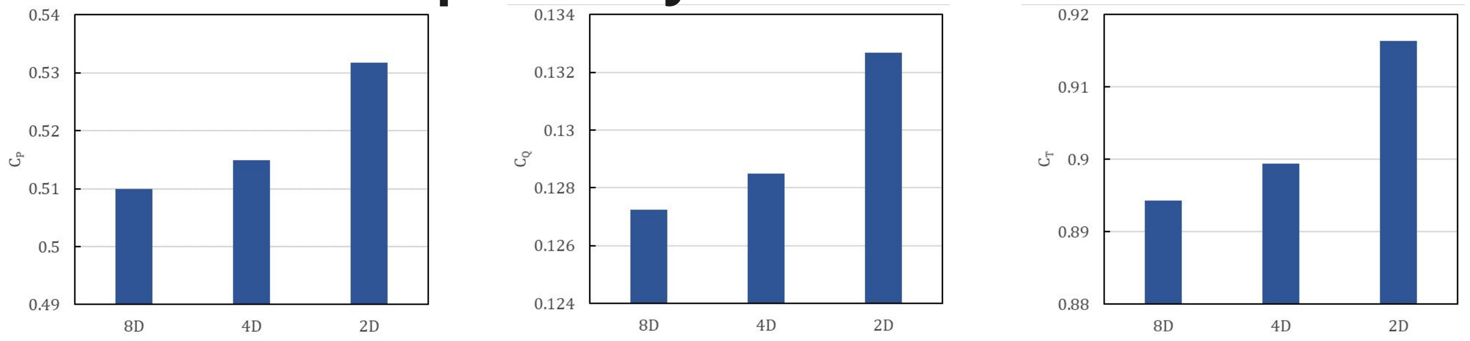
					Convergence							GCI
	2	-0.0008	0.0083	-0.0974	Oscillatory Convergence	3.3601	1	3.3601	-0.0001	0.05%	1.25	0.02%
	2	-0.0002	0.0021	-0.0974	Oscillatory Convergence	3.3601	1	3.3601	0.0000	0.01%	1.25	0.02%
	2	-0.0008	0.0084	-0.0981	Oscillatory Convergence	3.3499	1	3.3499	-0.0001	0.05%	1.25	0.01%



					Convergence							GCI
	2	-0.0008	0.0083	-0.1011	Oscillatory Convergence	3.3060	1	3.3060	-0.0001	0.05%	1.25	0.02%
	2	-0.0002	0.0021	-0.1011	Oscillatory Convergence	3.3060	1	3.3060	0.0000	0.01%	1.25	0.02%
	2	-0.0009	0.0084	-0.1018	Oscillatory Convergence	3.2961	1	3.2961	-0.0001	0.05%	1.25	0.01%

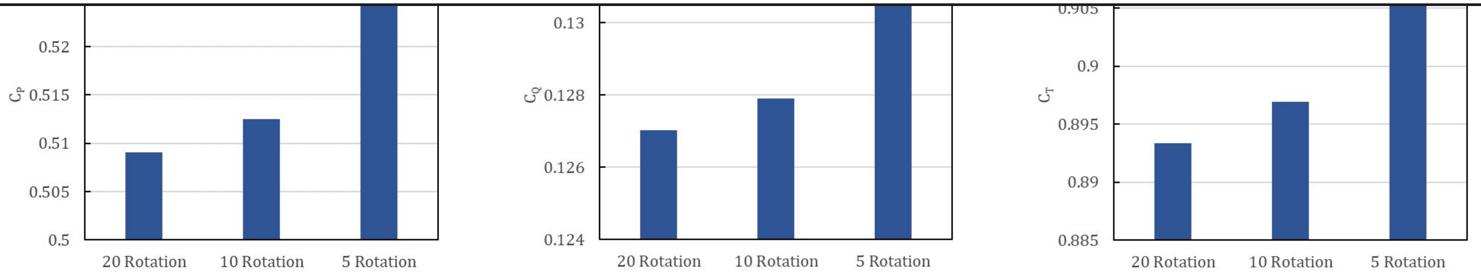
SNL-ARL MHKF1 - VERIFICATION AND UNCERTAINTY ANALYSIS

Number of Near Wake Panels Dependency



ϵ: Error between solutions
R_k: Convergence ratio
r_k: Refinement ratio
P_k: Order of accuracy
P_{kest}: Theoretical order of accuracy
δ: Error from Richardson Extrapolation
U_k: Uncertainty

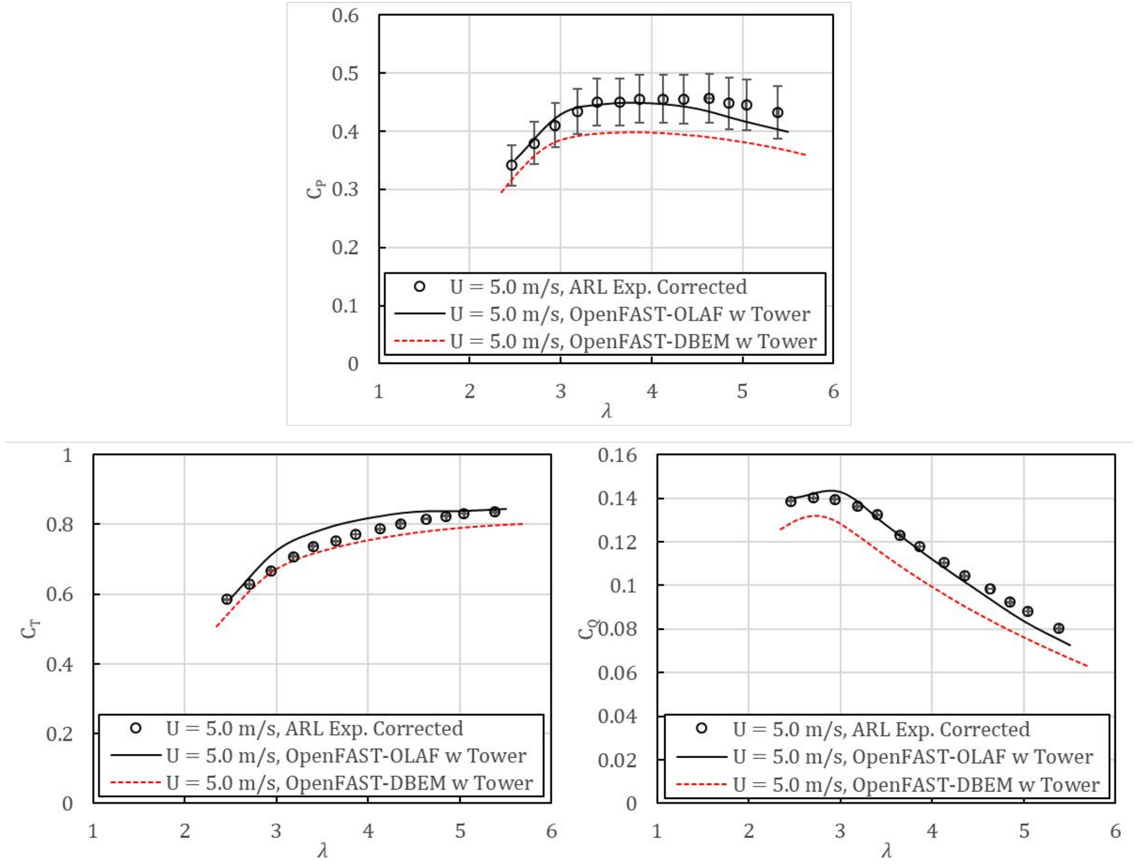
					Convergence							GCI
	2	0.0050	0.0168	0.2987	Monotonic Convergence	1.7430	1	1.7430	0.0021	0.60%	1.25	0.52%
	2	0.0013	0.0042	0.2987	Monotonic Convergence	1.7430	1	1.7430	0.0005	0.15%	1.25	0.52%
	2	0.0051	0.0169	0.3017	Monotonic Convergence	1.7288	1	1.7288	0.0022	0.61%	1.25	0.31%



					Convergence							GCI
	2	0.0035	0.0118	0.2985	Monotonic Convergence	1.7440	1	1.7440	0.0015	0.42%	1.25	0.37%
	2	0.0009	0.0029	0.2985	Monotonic Convergence	1.7440	1	1.7440	0.0004	0.10%	1.25	0.37%
	2	0.0036	0.0119	0.3001	Monotonic Convergence	1.7367	1	1.7367	0.0015	0.43%	1.25	0.21%

SNL-ARL MHKF1 - VALIDATION

BEM vs FVW



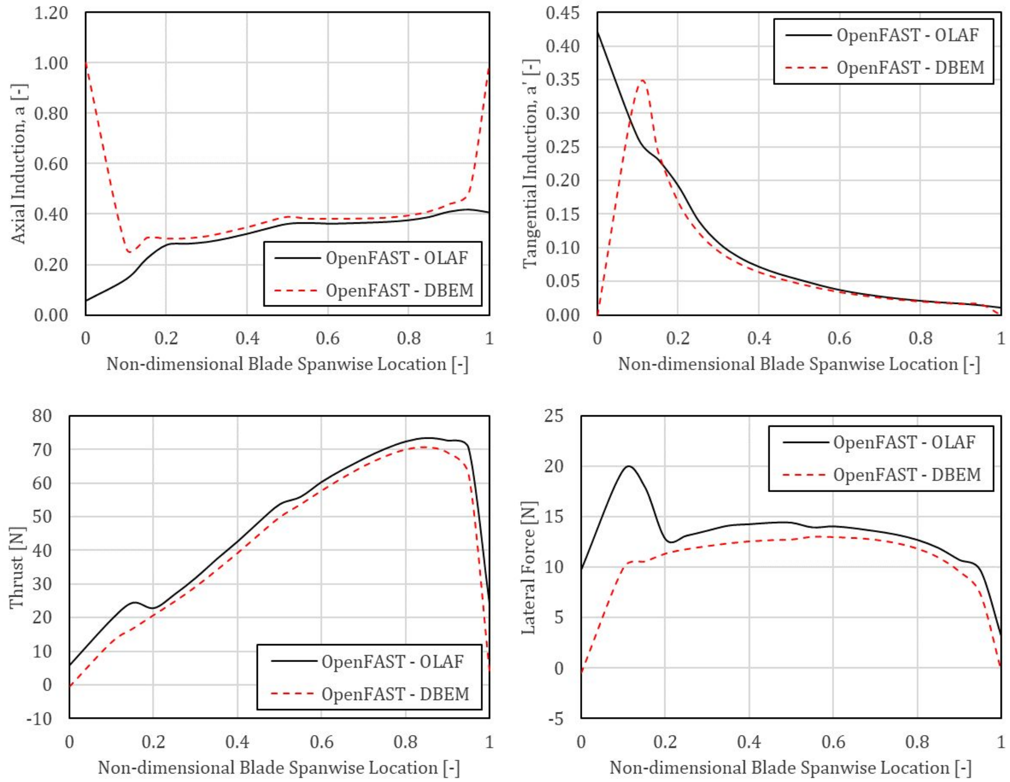
Turbine power, torque, and thrust coefficients curves estimated from the simulations using DBEM and FVW methods (red dashed line and red triangle, respectively) and blockage effect corrected measurement data (black empty circle)

In BEM,

Tangential induction (a') is set to 0 at the root and tip

Axial induction (a) is set to 1 at the root and tip

@TSR = 4.0

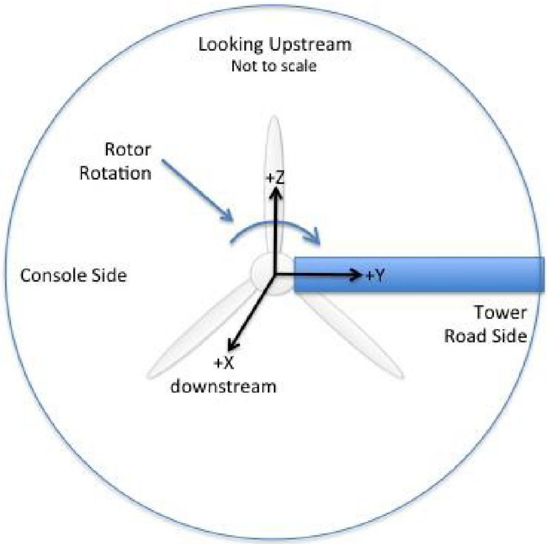


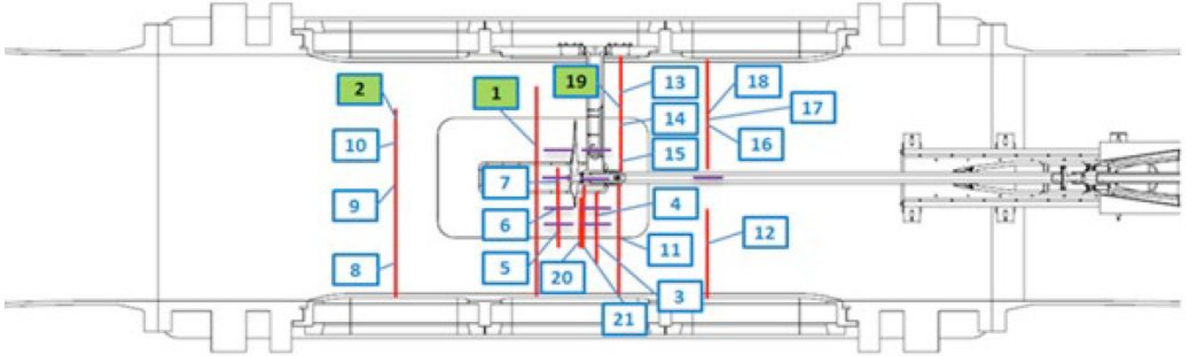
Local axial and tangential induction factors, and thrust and lateral forces acting on each blade segment along the blade spanwise direction at TSR of 4.0 estimated by FVW and BEM methods.

SNL-ARL MHKF1 - VALIDATION

LDV data - Phase averaged velocity profiles

- Inflow
- Rotor wake
- Tower wake



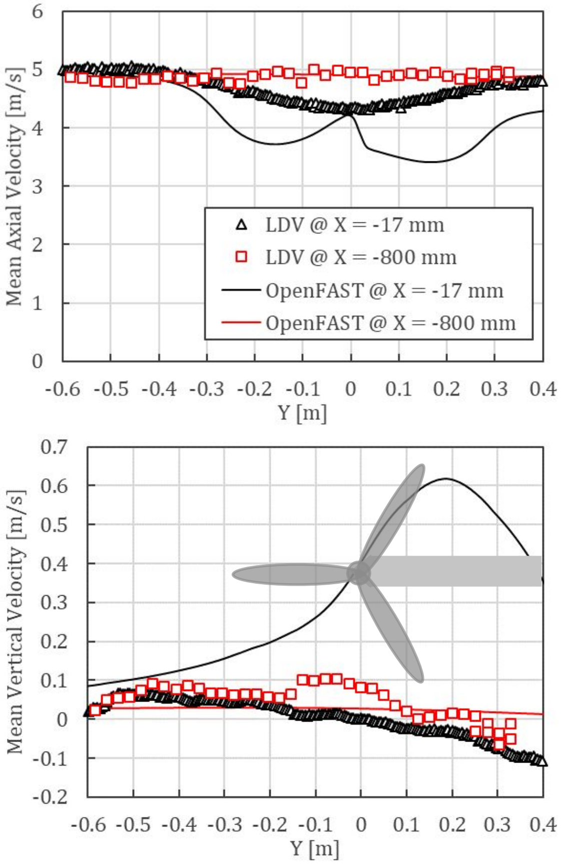


LDV Survey No.	X (mm)	X/D	Notes
1	-51	-0.1	Bare Hub Inflow Survey
2	-800	-1.4	Bare Hub Inflow Survey
3	135	0.2	
4	135	0.2	
5	-17	0.0	
6	-17	0.0	
7	-17	0.0	
8	-800	-1.4	No Encoder Data
9	-800	-1.4	No Encoder Data
10	-800	-1.4	No Encoder Data
11	216	0.4	
12	5740	10.0	Coinc. w/ PIV meas.
13	248	0.4	
14	248	0.4	No Encoder Data
15	248	0.4	
16	5740	10.0	Centerline Height
17	5740	10.0	1.9 cm above Centerline
18	5740	10.0	1.9 cm below Centerline
19	248	0.4	Bare Hub Surv. DS of Tower
20	64	0.1	Coinc. w/ SPIV meas.
21	89	0.2	Coinc. W/ SPIV meas.

SNL-ARL MHKF1 - VALIDATION

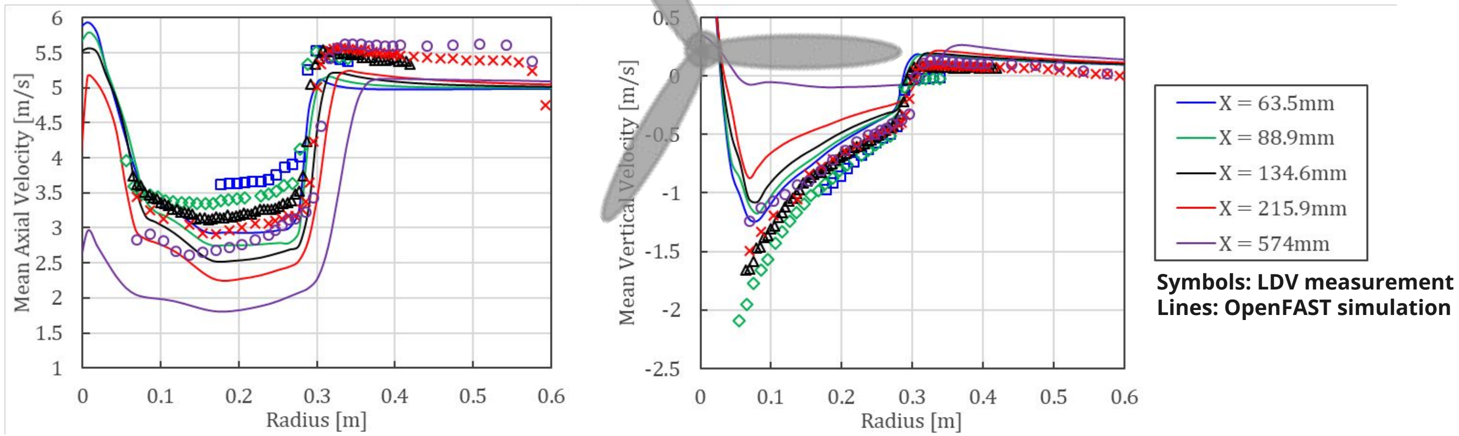
Inflow

- Rotor mean velocity inflow profiles measured with LDV
  - @ X = -800 and -17 mm

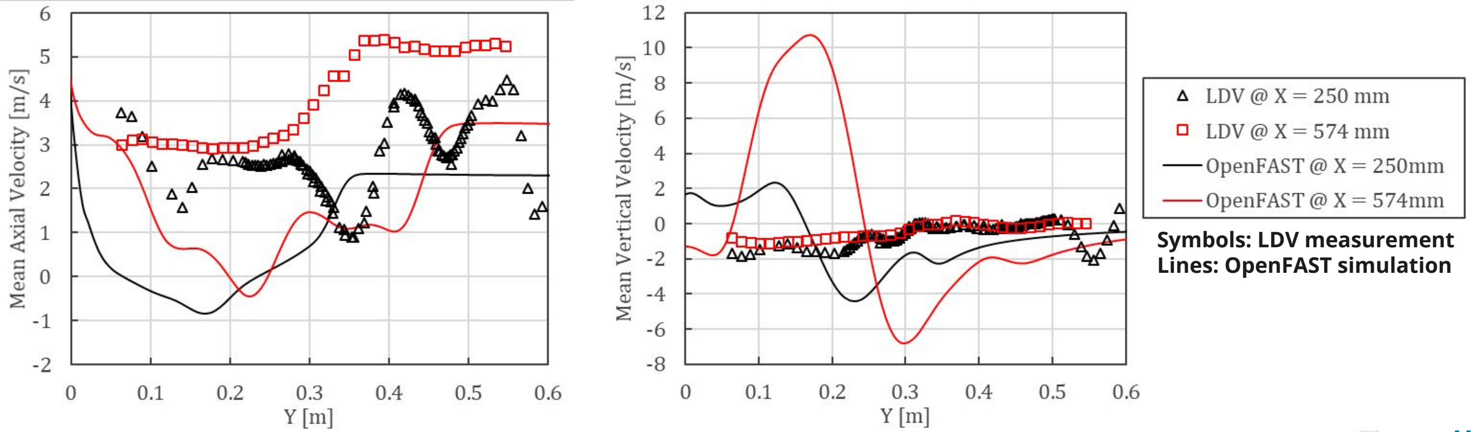


Rotor and Tower Wake

- Mean velocity profiles downstream of the rotor
  - @ X = 63.5 – 574 mm (0.1D – 10D)



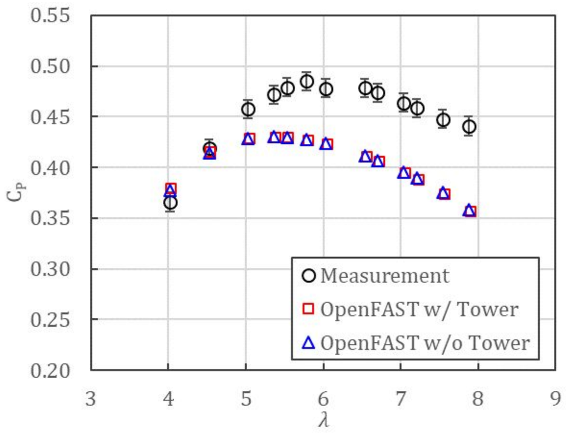
- Mean velocity profiles in the tower wake
  - @ X = 250 and 574 mm (0.4D and 1.0D)

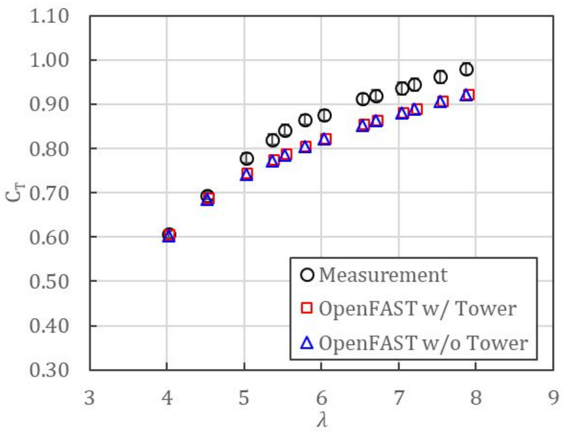


OTHER ROTORS - VALIDATION

Oxford Reference Rotor

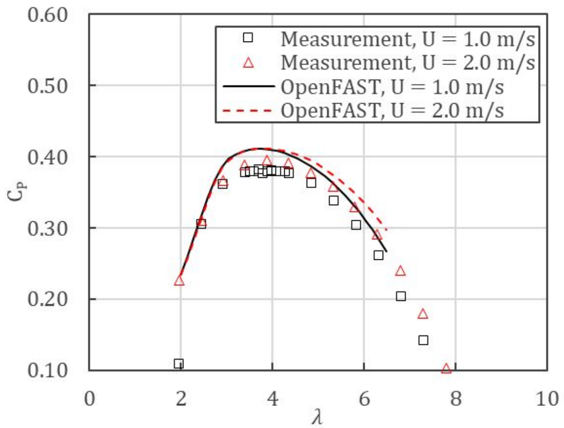
- Single tow speed: 1.0 m/s
- Low blockage level (3.05%),
- Low and elevated turbulence level (3.1%)
- OpenFAST run: DBEM w/ and w/o tower in low turbulence flow

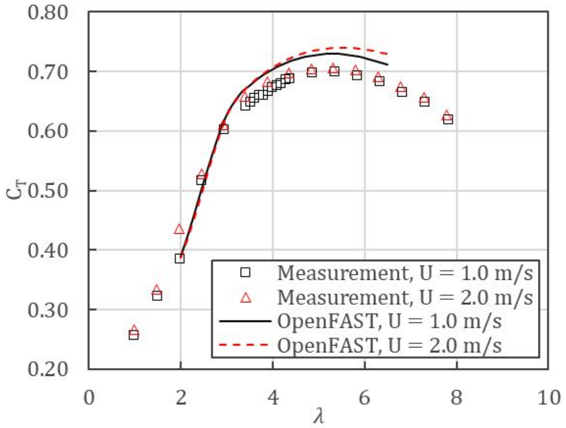


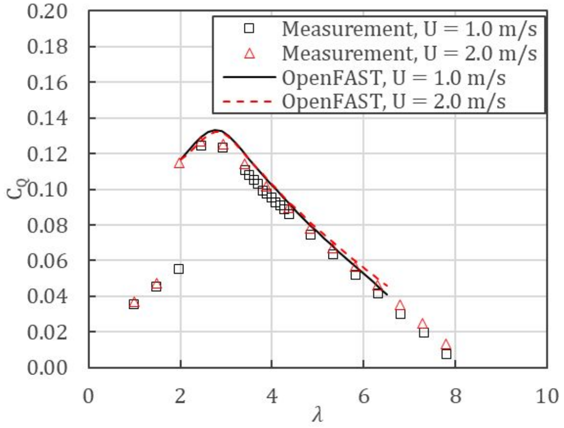


AMEC OSTEC Rotor

- Towing speeds: 0.4 – 2.0 m/s
- Blockage corrected coefficients
- OpenFAST run: DBEM without tower effect







CONCLUSIONS

- Successful V&V Foundation: This work successfully established a V&V foundation for OpenFAST in MHK applications.
  - Verification: Systematic convergence studies have quantified the numerical uncertainty of the FVW model for key parameters like time step and wake panel discretization.
  - Validation: The models show good predictive capability for integral performance coefficients (Cp, Ct, Cq) across multiple experimental datasets (ARL/SNL, TTB, UNH/AMEC).

- Key Model Gaps Identified: The validation process clearly identified the current limitations and primary sources of model error.
  - Flow Confinement: OpenFAST does not capture the flow acceleration (blockage effect) near tunnel walls, a critical component of the experimental environment.
  - Tower Wake Physics: The model significantly misrepresents the tower wake. This is a direct result of the current one-way tower influence model, which prevents the rotor wake from interacting with the flow around the tower.
  - Operating Extremes: The models currently fail to capture performance degradation from severe cavitation breakdown and Reynolds number dependency at low TSRs.

FUTURE WORK

- Improve Tower Modeling:
  - Enhance the tower model to include two-way hydrodynamic interaction. This is the highest priority for accurately predicting the tower wake and its impact on turbine loading and performance.

- Implement Flow Confinement Model: Integrate a blockage correction or flow confinement model into OpenFAST to enable more accurate validation against data from water tunnels and towing tanks.

- Quantify Model Input Uncertainty:
  - Expand the uncertainty analysis to include key input parameters.
  - Propagate the uncertainty from the experimental freestream velocity (U_∞) to quantify its significant impact on C_P and C_T.
  - Assess the model form uncertainty associated with using 2D foil polar data and empirical corrections for 3D rotational flow.

- Expand Blade Load Validation:
  - Conduct detailed validation of predicted local blade loads (e.g., flapwise and edgewise bending moments) against the comprehensive datasets from the TTB Project and UNH/AMEC turbine experiments.

REFERENCES

1) Thacker, B. H., Doebling, S. W., Hemez, F. M., Anderson, M. C., Pepin, J. E., & Rodriguez, E. A. (2004). "Concepts of model verification and validation." Los Alamos National Laboratory Report, LA-14167-MS.
2) Roache, P. J. (1998). "Verification of codes and calculations." AIAA Journal, vol. 36, no. 5, pp. 696-702.
3) Stern, F., Wilson, R. V., Coleman, H. W., & Paterson, E. G. (2001). "Comprehensive approach to verification and validation of CFD simulations—part 1: methodology and procedures." Journal of Fluids Engineering, vol. 123, no. 4, pp. 793-802.
4) Xing, T., & Stern, F. (2010). "Factors of safety for Richardson extrapolation." Journal of Fluids Engineering, vol. 132, no. 6, 061403.
5) Fontaine, A. A., et al. (2020). "Performance and wake flow characterization of a 1:8.7-scale reference USDOE MHKF1 hydrokinetic turbine to establish a verification and validation test database." Renewable Energy, vol. 159, pp. 451-467. https://doi.org/10.1016/j.renene.2020.05.166.
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8) Andersen, M. N. (2024). "Design of an Axial-Flow Tidal Turbine Test Bed and Initial Validation and Performance Testing with 1:5 Scale MHKF1 Rotor" (Master's Thesis). University of New Hampshire. Retrieved from https://scholars.unh.edu/thesis/1875.

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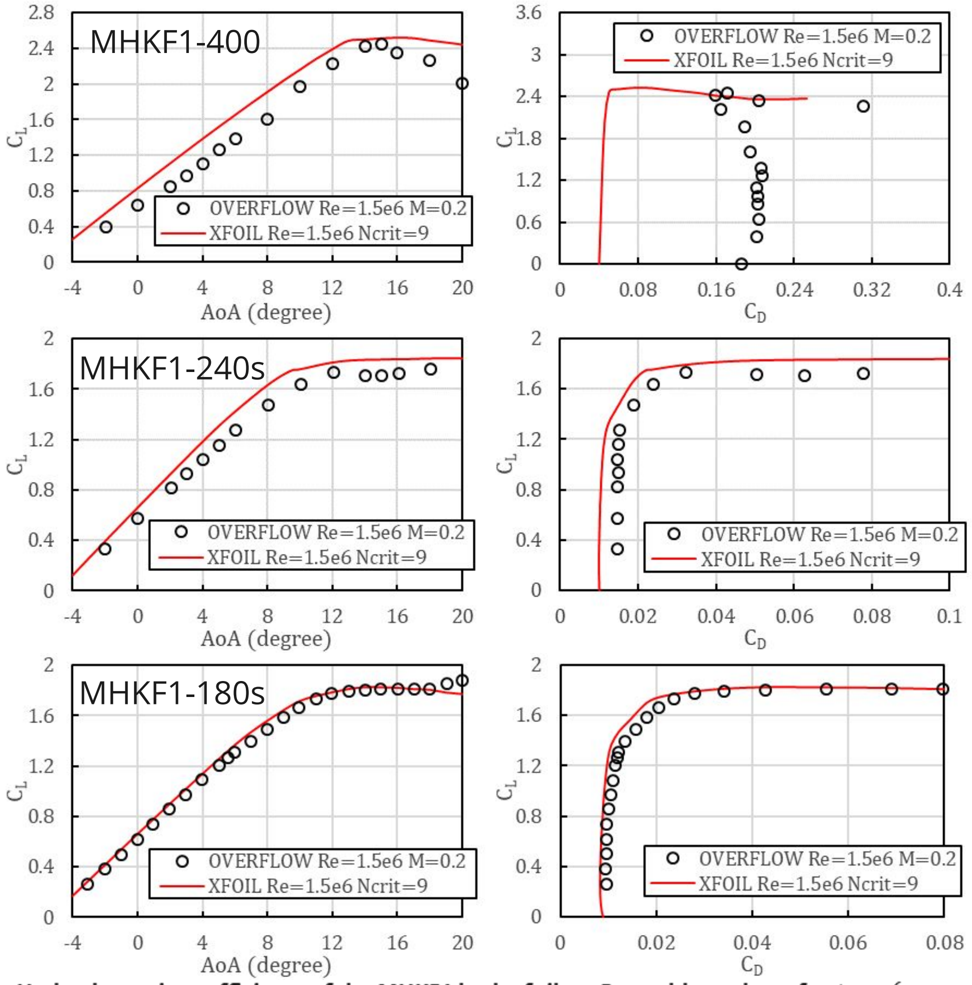
MHKF1 - MODELING

Foil Polar Data

- Obtain C_L, C_D, C_M and $C_{P,min}$ using 2-D panel method code, XFOIL
- Extrapolate data from AoAs of -10° to 30° to cover a range of -180° to 180° using Viterna method
- Limitation of XFOIL
  - Diverge at low Reynolds number < 300,000
  - Unable to resolve flat and sheepsfoot trailing edge
  - Large error in drag of thick flat-back foil
  - Only applicable to low turbulence intensity < 1%

Code-to-code comparison

- XFOIL vs OVERFLOW



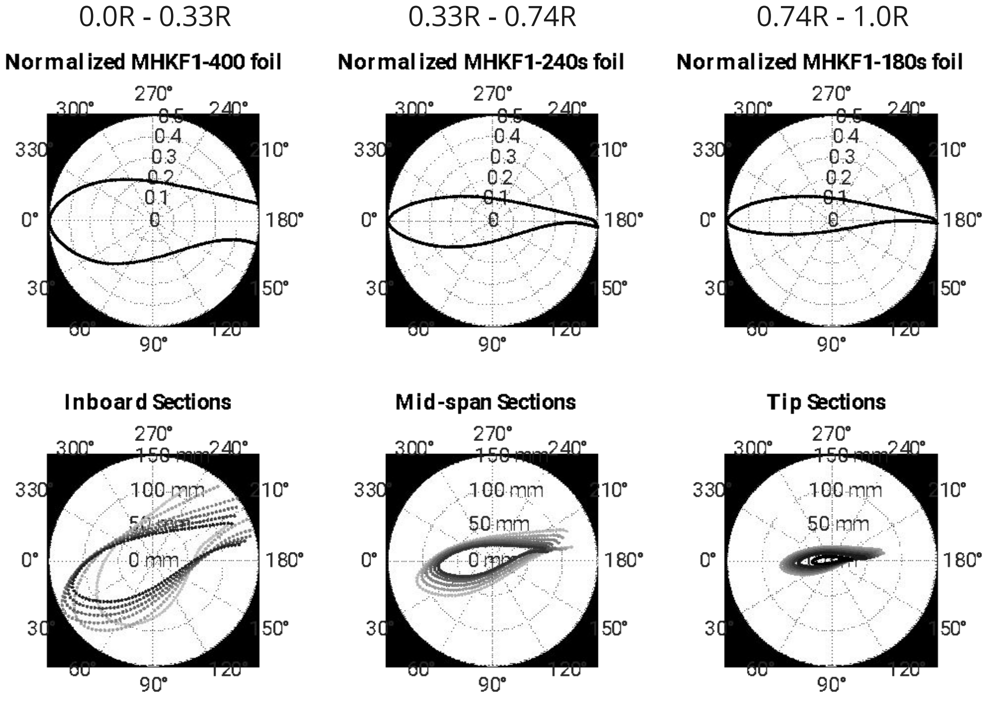
Hydrodynamic coefficients of the MHKF1 hydrofoils at Reynold number of 1.5×10^6 estimated by OVERFLOW (black empty circle, Shiu et al. 2012) and XFOIL (red solid line)

- Shiu, Henry, C. P. Van Dam, Erick Johnson, Matthew Barone, Ryan Phillips, William Straka, Arnold Fontaine, and Michael Jonson. "A design of a hydrofoil family for current-driven marine-hydrokinetic turbines." International Conference on Nuclear Engineering. Vol. 44984. American Society of Mechanical Engineers, 2012.

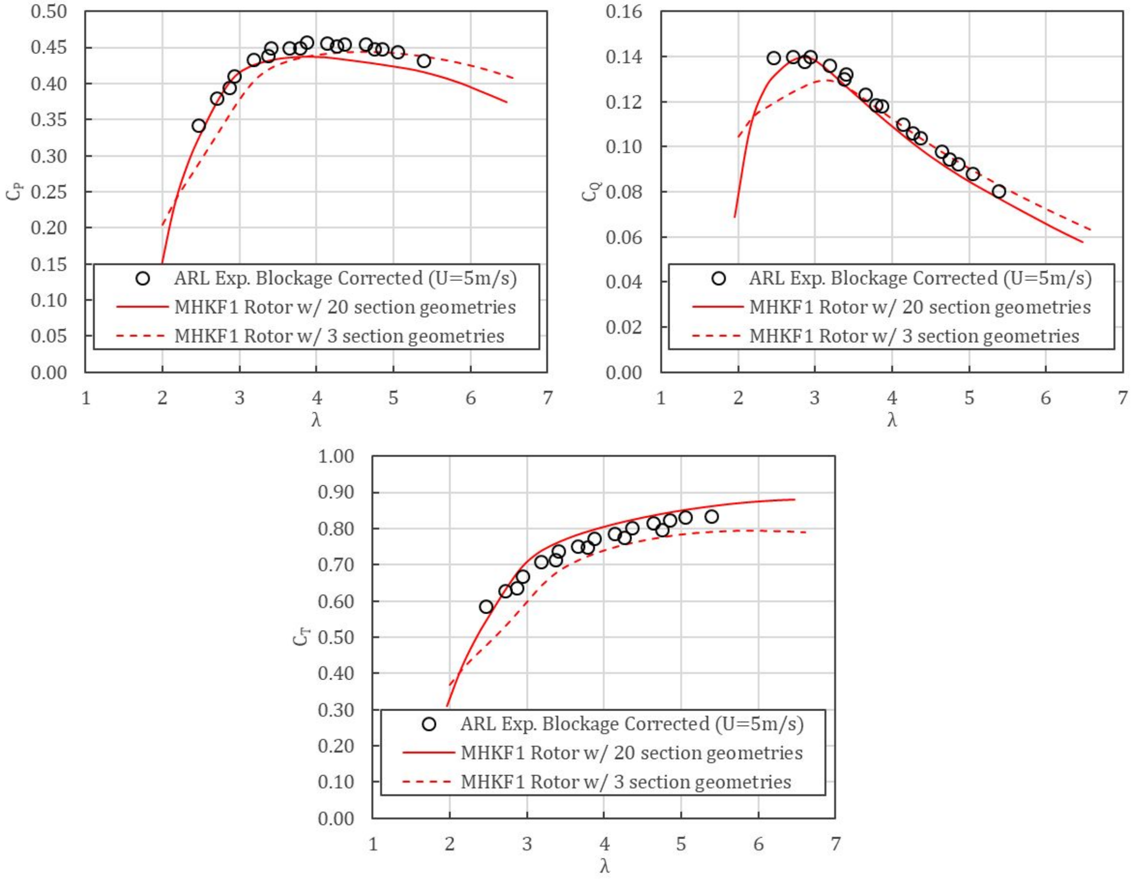
MHKF1 - MODELING

Effect of the Number of Blade Section Geometries for Polar Data

- 3 sections: MHKF1-400, 240s, 180s
- 20 sections Include transitional sections



Normalized MHKF1 hydrofoil sections (upper) and discretized 20 blade sections at inboard, mid-span, and tip areas (lower).



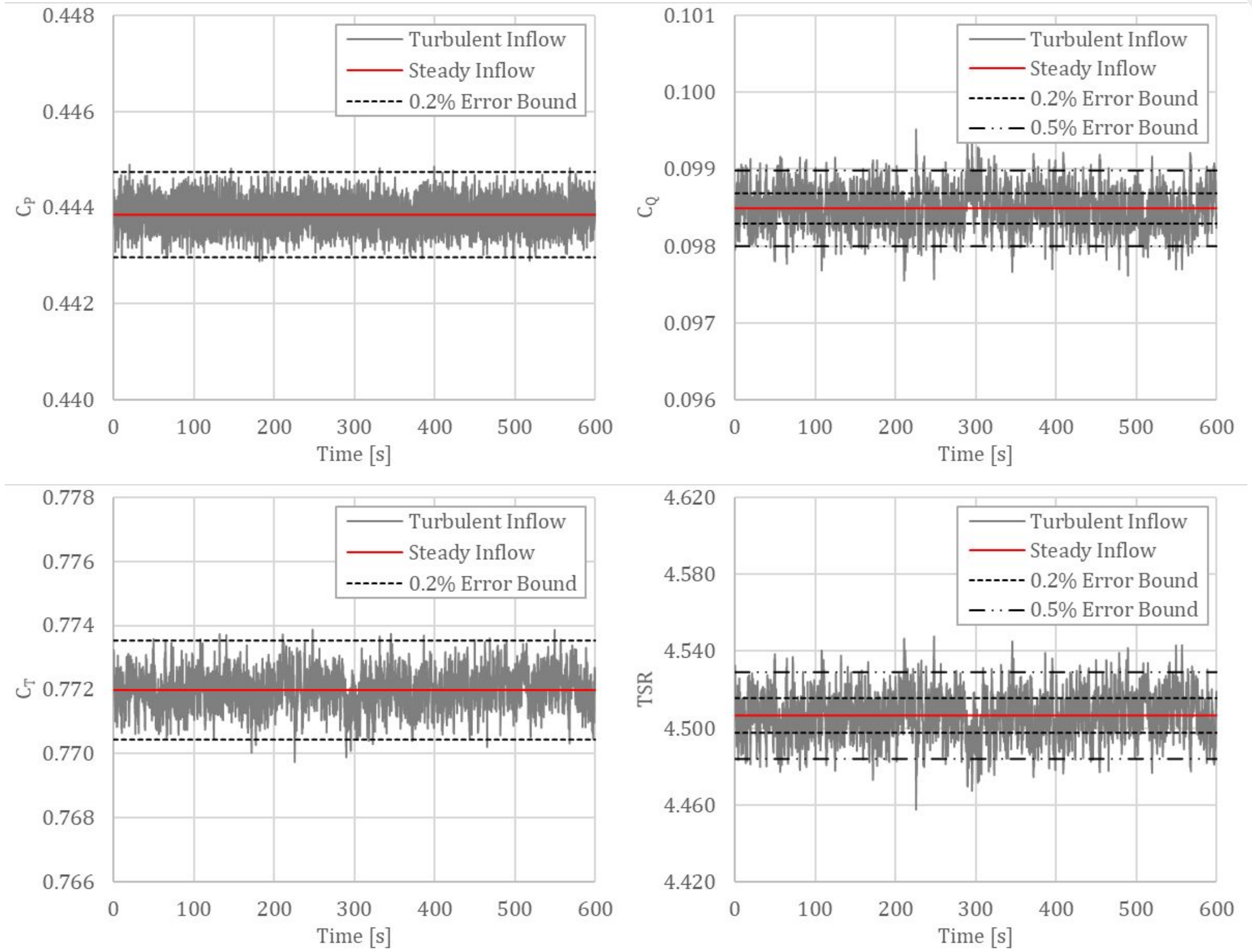
Turbine power, torque, and thrust coefficients estimated from the simulations using 20 and 3 blade section geometries for polar data (red solid and dashed line, respectively) and blockage effect corrected measurement data (black empty circle)

Effect of Turbulence

- $\bar{U}$ = 5.0 m/s
- TSR = 4.51
- T_i = 0.3% modeled by TurbSim
- 10 min simulations based on IEC TS 62600-3

Variation of C_P and C_T is within 0.2%

Variation of C_Q is within 0.5%

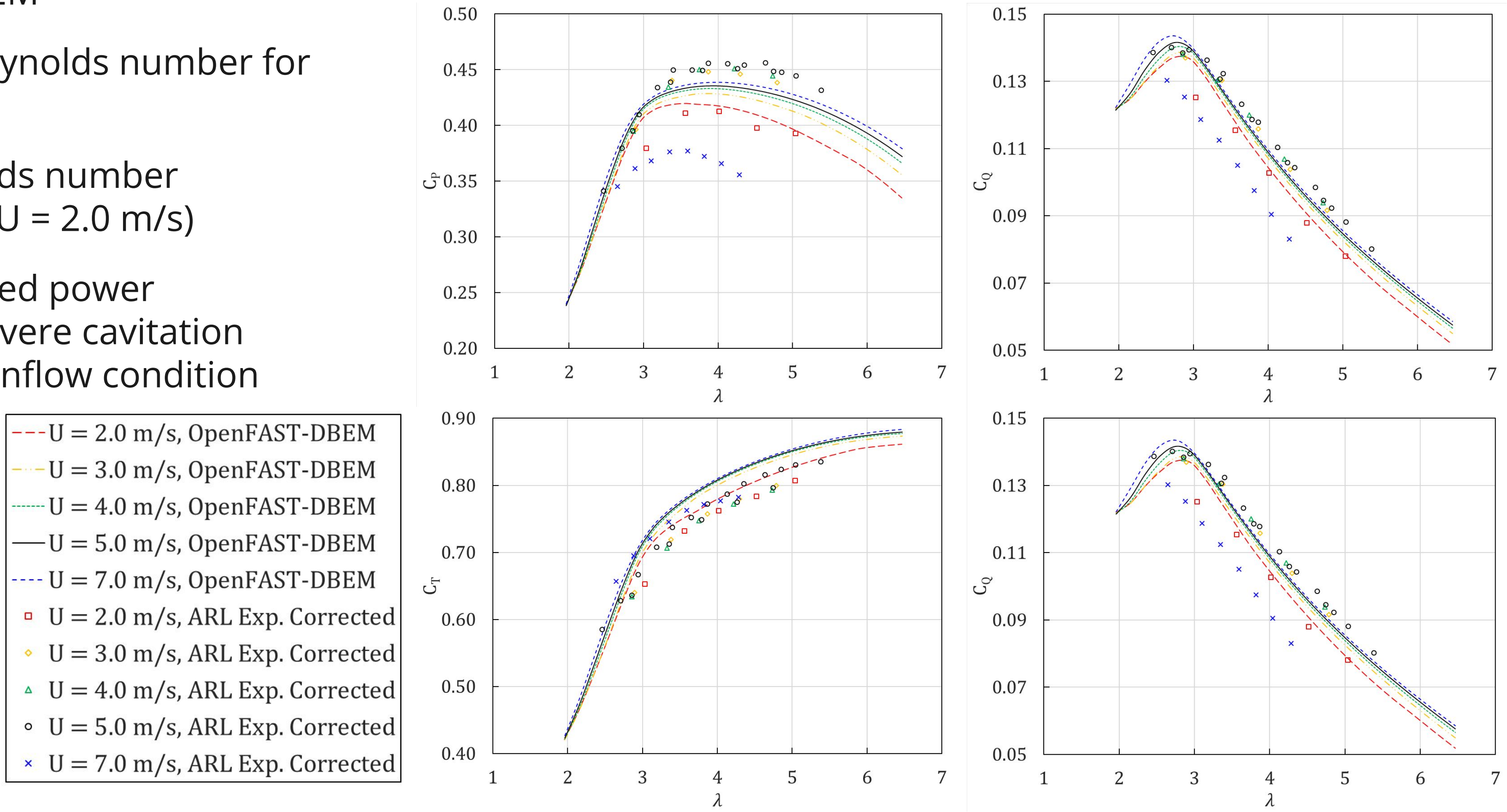


10 minutes power, torque, and thrust coefficients variation estimated from the simulation with and without turbulent inflow

MHKF1 - VALIDATION

Reynolds Number Dependency

- U = 2.0 – 7.0 m/s using DBEM
- No significant impact of Reynolds number for U = 3.0 - 5.0 m/s
- Fails to capture the Reynolds number dependency at lower TSR (U = 2.0 m/s)
- Unable to simulate degraded power performance due to the severe cavitation breakdown at the 7.0 m/s inflow condition



Predicted coefficient curves of power (top left), thrust (top right), and torque (bottom left) obtained from OpenFAST simulations and blockage corrected measurement data

MHKF1 - VALIDATION

Cavitation

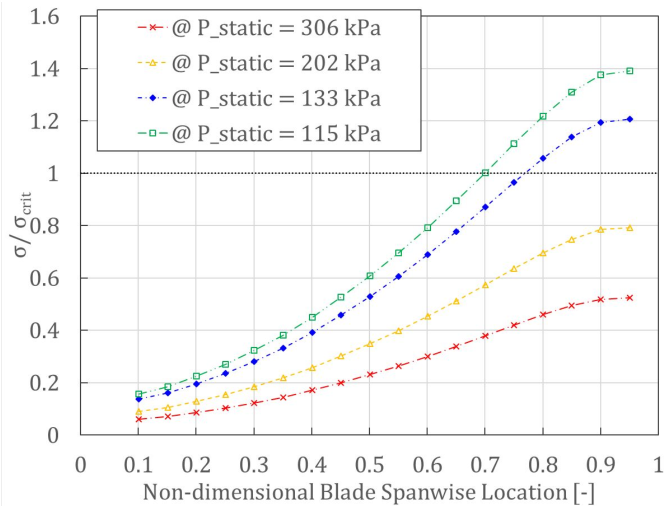
- Cavitation occurs when the local cavitation number is greater than or equal to the critical cavitation number
- Critical cavitation number is based on the minimum pressure coefficient of the blade section

$$\sigma_{crit} = \frac{(P_{atm} + \rho g h) - P_{vap}}{\frac{1}{2}\rho V_{rel}^2}$$

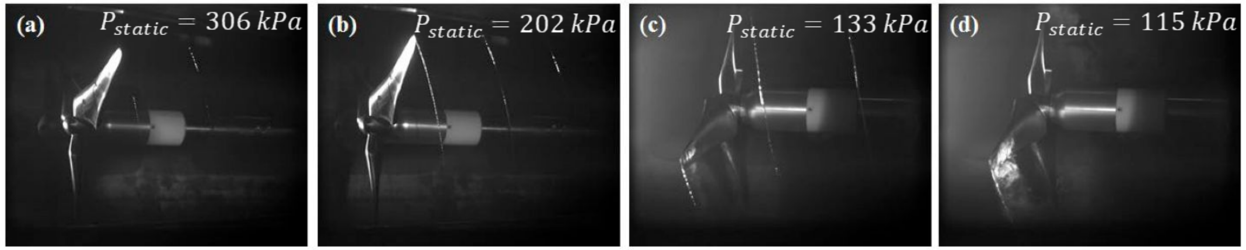
$$\sigma = \frac{(P_{atm} + \rho g h) - P_{Local}}{\frac{1}{2}\rho V_{rel}^2} = -C_{P,min}$$

- At static pressure of 115, 133, 202, and 306 kPa

Cavitation $\sigma_{crit} < \sigma$ or $\frac{\sigma}{\sigma_{crit}} > 1$



Estimated ratio of local cavitation number to critical cavitation number at four different static pressure conditions along the blade (U=4.0m/s, TSR=3.91). A ratio greater than one indicating the occurrence of cavitation.



Photographs of intermittent tip vortex cavitation (a), steady tip-vortex cavitation (b), blade cavitation inception near the cavitation breakdown point (c), and developed blade cavitation during cavitation breakdown (d) (Fontaine et al., 2020)