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Validation of Blade Element Momentum & Free Vortex Wake Methods with Water Tunnel Data for a Scaled Marine Turbine Rotor

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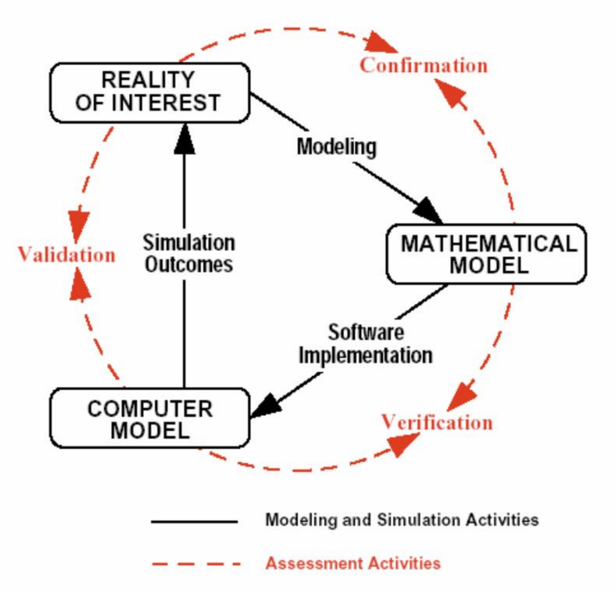
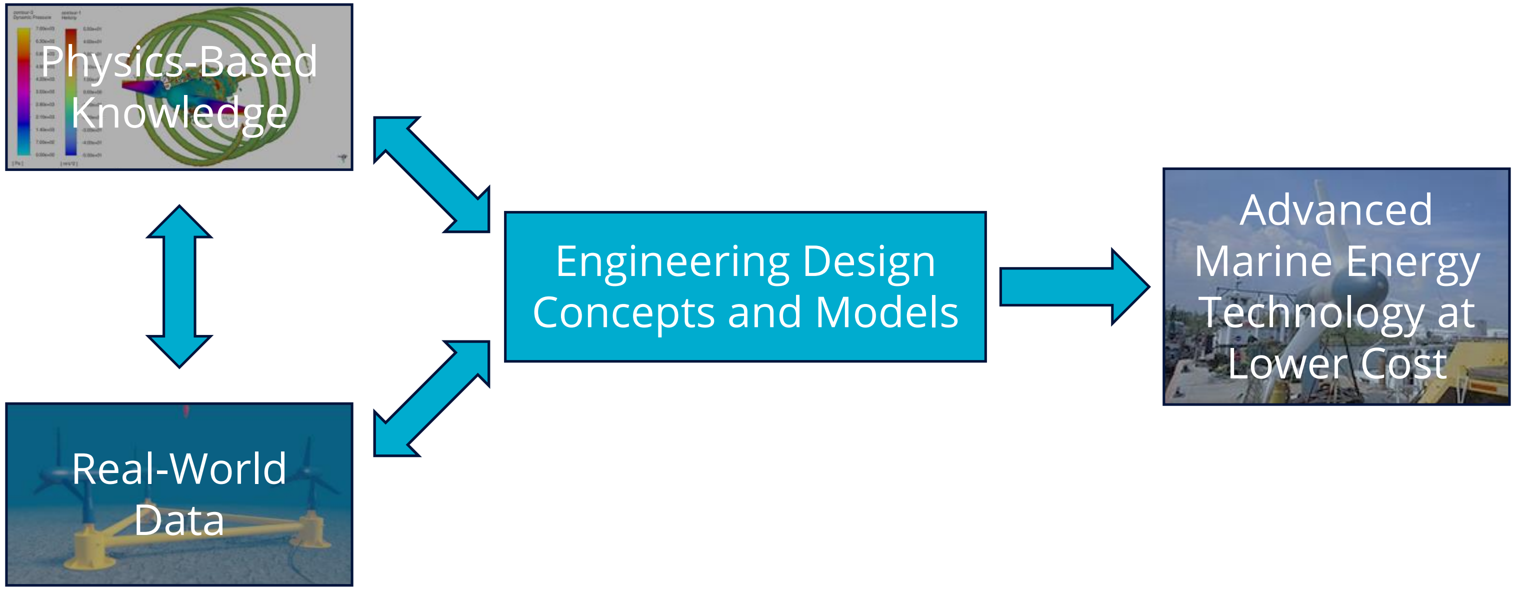
BACKGROUND

- 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 understand 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).

TURBINE ROTOR

Scaled-Model MHKF1 Rotor

- A 1:8.7 scale model of the 5.0-m-diameter USDOE-MHKF1 rotor (D_{Rotor} = 574.2 mm)
- Tested at Garfield Thomas Water Tunnel (GFWT) at the Applied Research Lab, Penn State University (test section: D = 1.22 m, L = 4.27 m)

Test and simulation

- U = 2.0 – 7.0 m/s
- TSR = 1.0 – 10.0
- Measurements:
  - LDV, PIV, and SPIV for a flow field quantification
  - Turbine sound
  - Powering performance
  - Cavitation
  - Driveshaft loading, Blade strain, and tower pressure
  - Oil-paint flow visualization

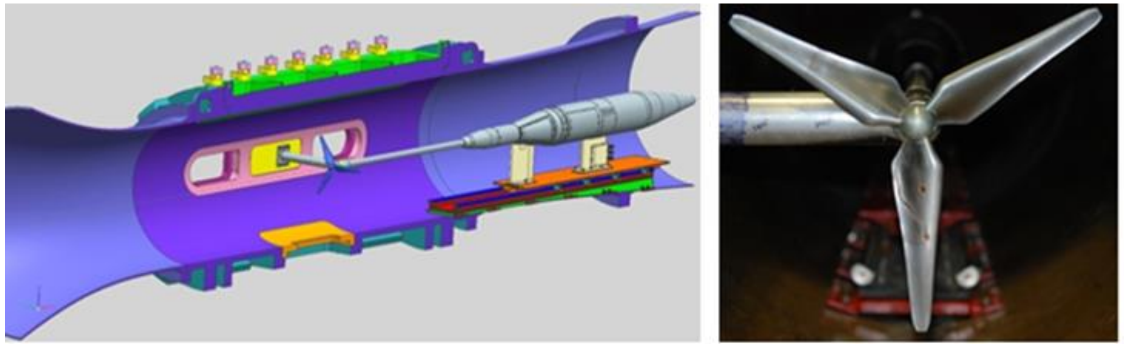
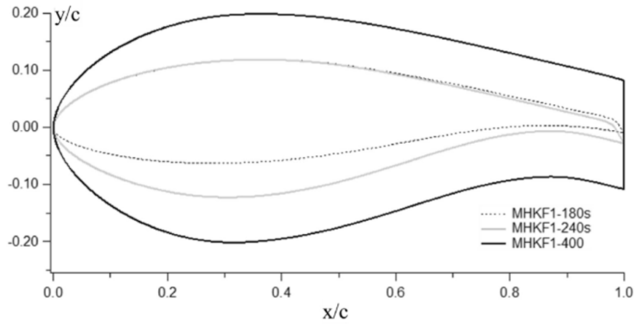
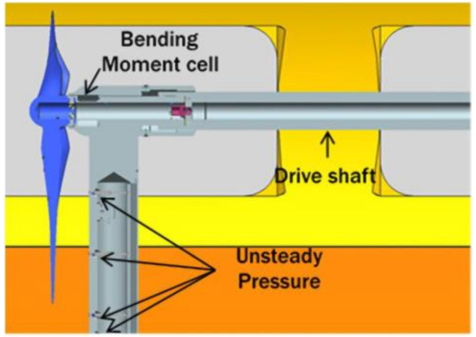


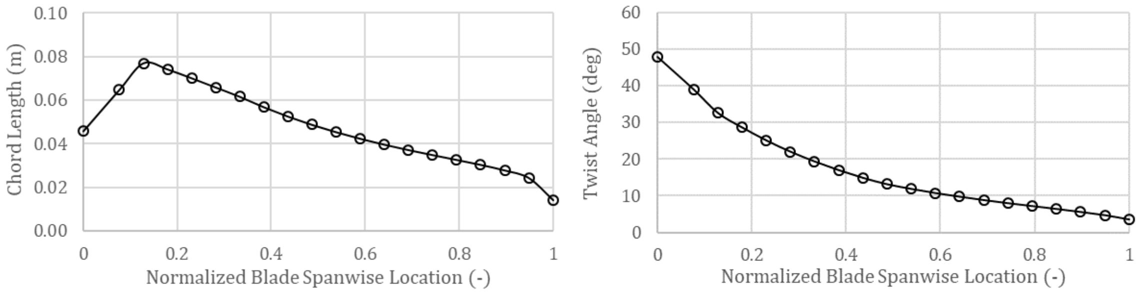
Illustration of the model rotor and dynamometer installed in the GTWT test section, and a photograph of the installed rotor (Fontaine et al., 2020)



MHKF1 family of hydrofoils with anti-singing (sheepsfoot profile) and flatback trailing edges



Close-up view of the turbine-nacelle-tower-driveshaft assembly (Fontaine et al., 2021)



Blade section chord length and twist angle along the spanwise location of the blade

- A. A. Fontaine, W. A. Straka, R. S. Meyer, M. L. Jonson, S. D. Young, and V. S. Neary, "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, 2020, doi: 10.1016/j.renene.2020.05.166.

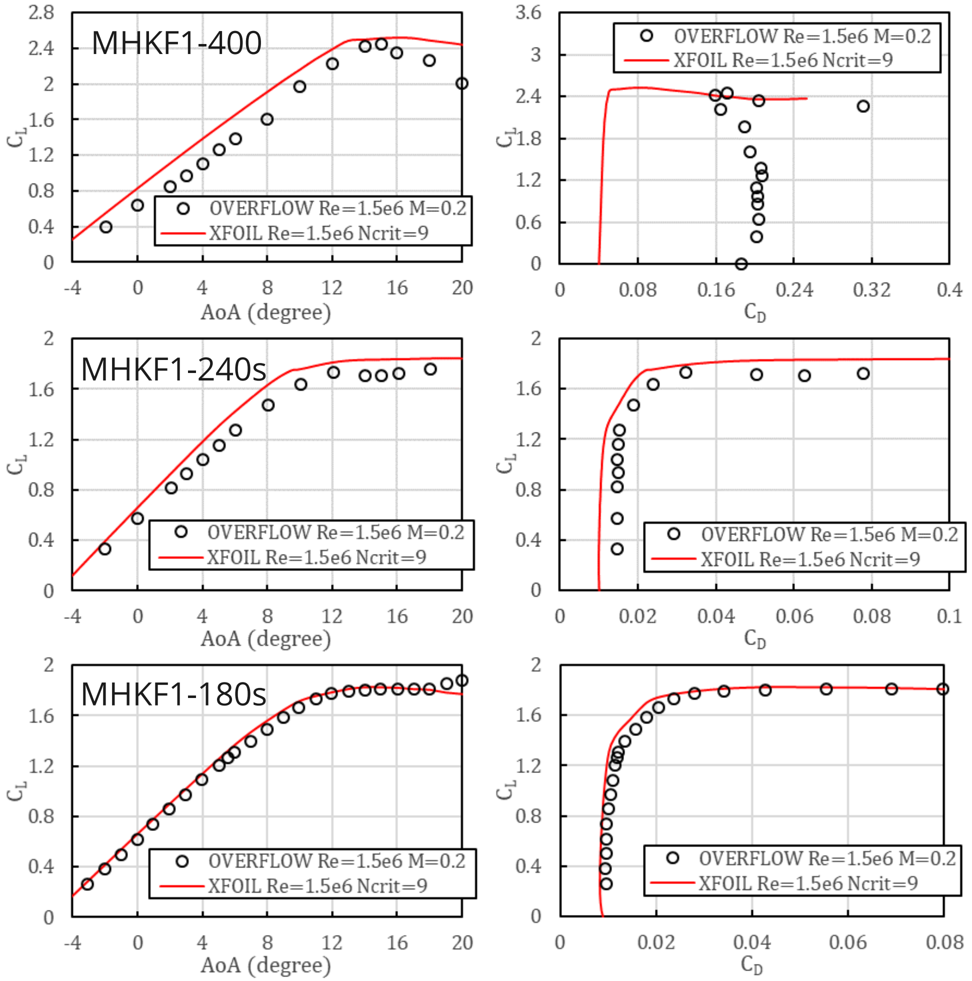
MODELING

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



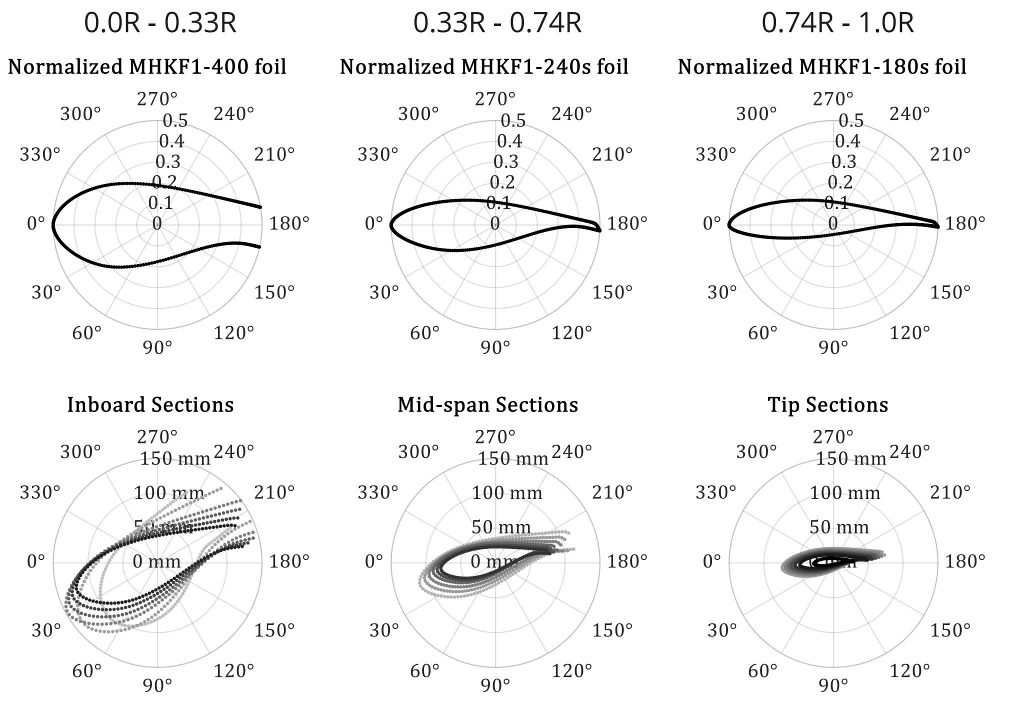
Hydrodynamic coefficients of the MHKF1 hydrofoils at Reynold number of 1.5×10^6 estimated by OVERFLOW (black empty circle, Shiu et al. 2012) and XFOIL (red solid line)

- 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.

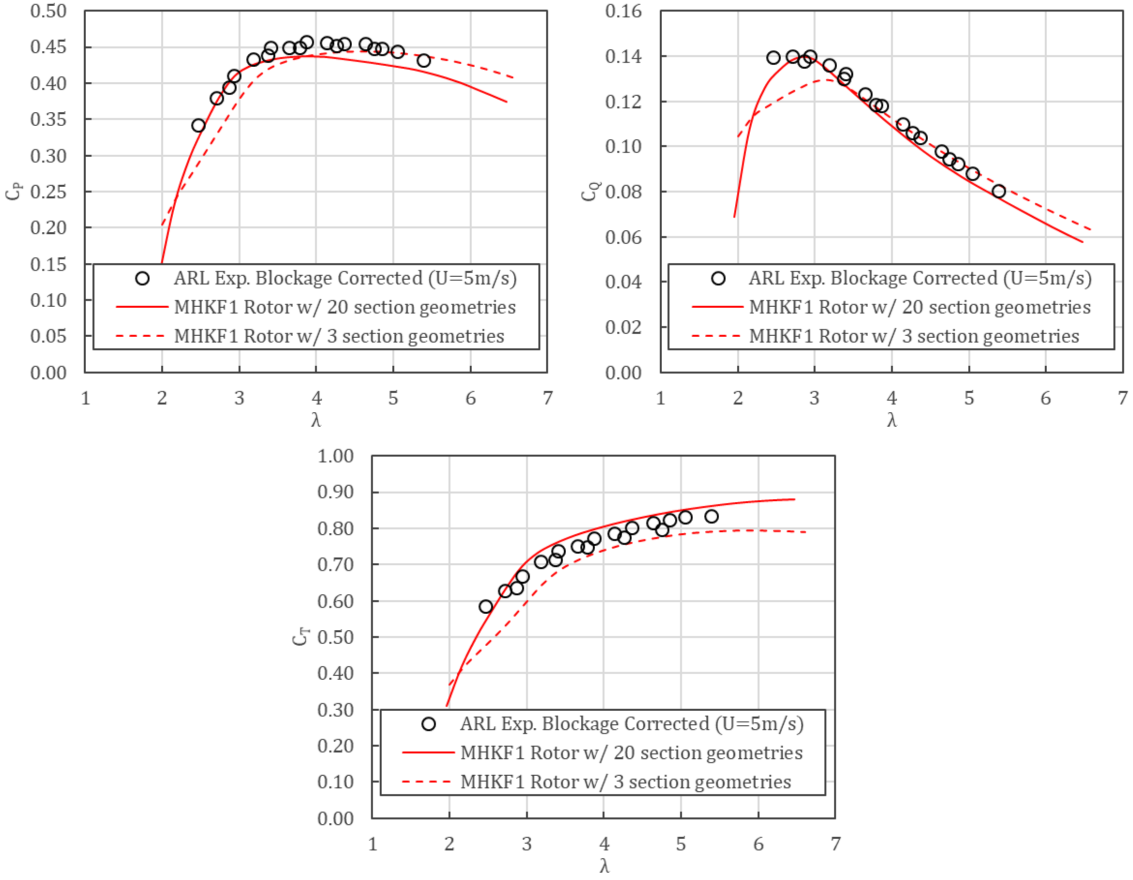
MODELING

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)

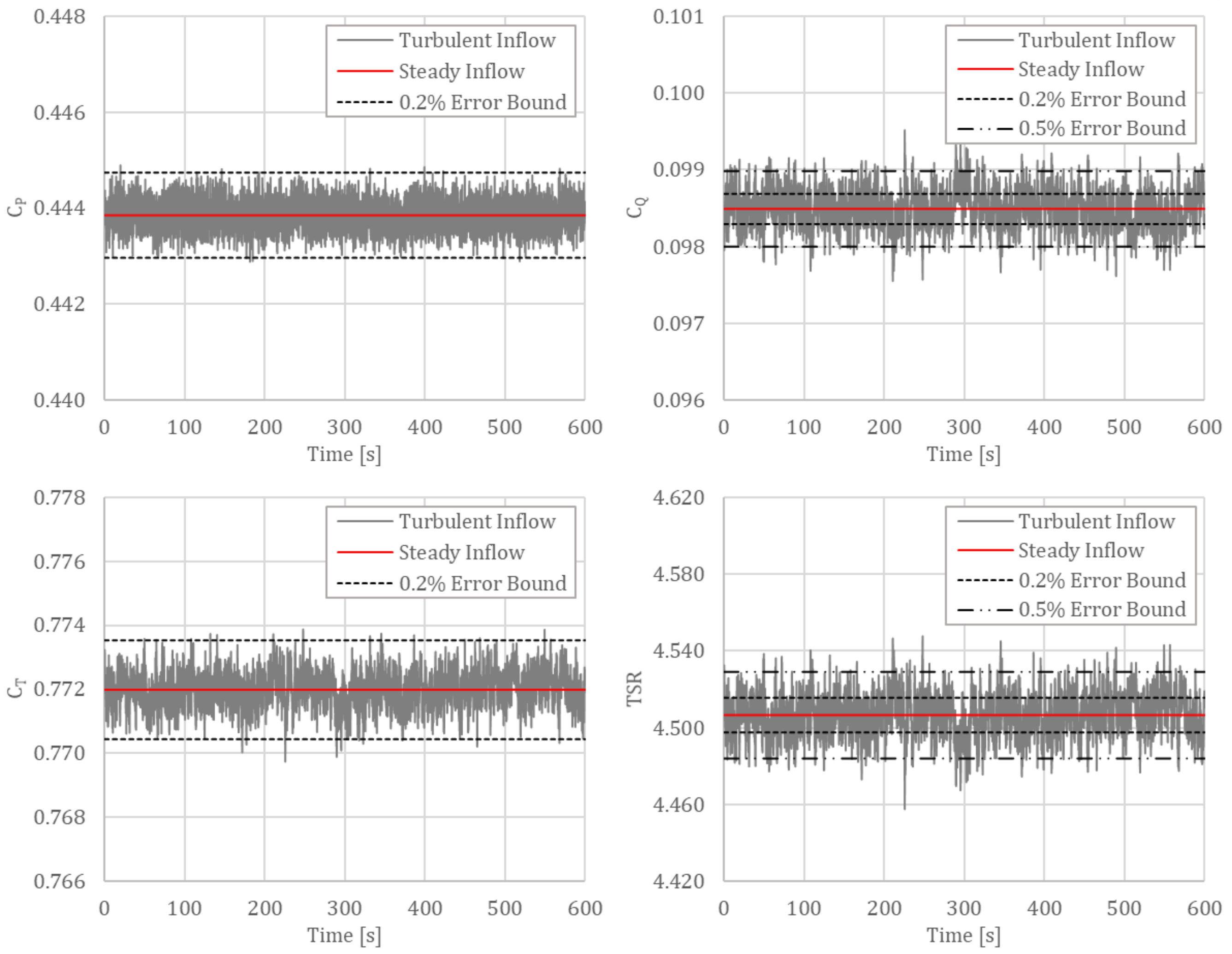
MODELING

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

VERIFICATION AND UNCERTAINTY ANALYSIS

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

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

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

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

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

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

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

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

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

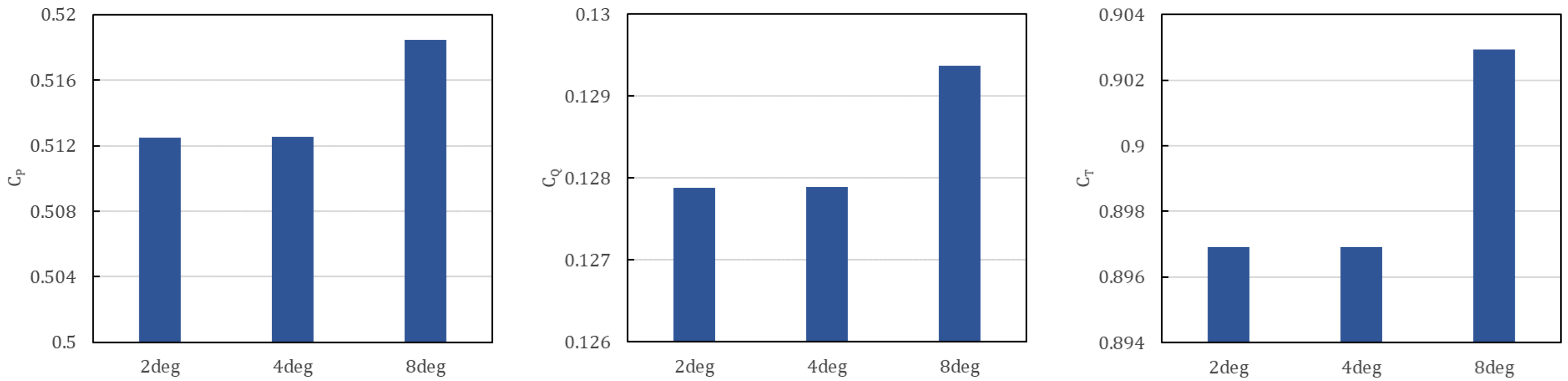
GCI: Grid convergence index based on the safety factor

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.

VERIFICATION AND UNCERTAINTY ANALYSIS

Time Step Size Dependency



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

	r_k	ϵ_{21}	ϵ_{32}	R_k	Convergence	P_k	P_{kest}	P	δ	U_k
C_P	2	6.0099E-05 (-0.012%)	5.9309E-03 (-1.157%)	1.0133E-02	Monotonic Convergence	6.6248	1	6.6248	6.1523E-07	0.0007%
C_Q	2	1.4997E-05 (-0.012%)	1.4800E-03 (-1.157%)	1.0133E-02	Monotonic Convergence	6.6247	1	6.6247	1.5353E-07	0.0002%
C_T	2	-8.8474E-06 (0.001%)	6.0195E-03 (-0.671%)	-1.4698E-03	Oscillatory Convergence	-	1	-	-	-

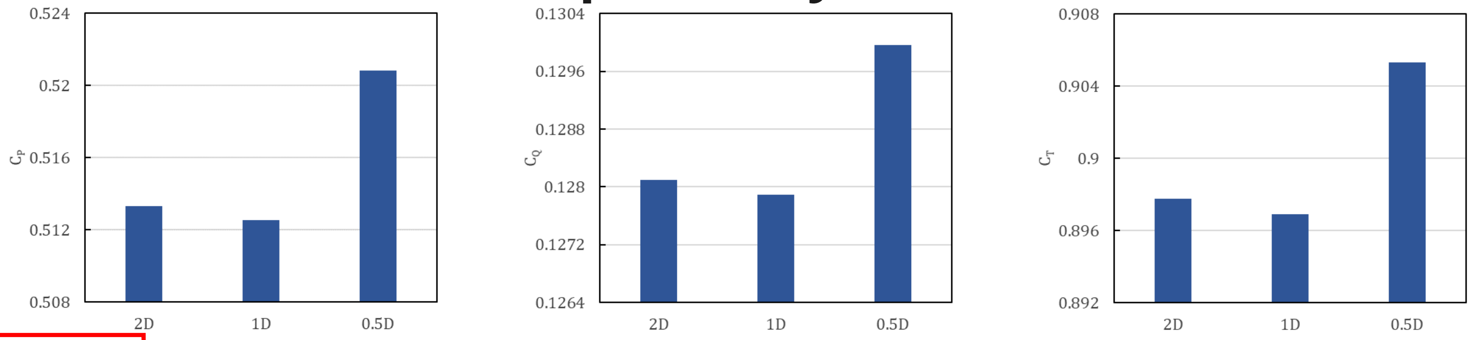
ϵ: Error between solutions
R_k: Convergence ratio
r_k: Refinement ratio
P_k: Order of accuracy
P_{kest}: Theoretical order of accuracy
δ: Error from Richardson Extrapolation
U_k: Uncertainty

Time step size corresponding to the **4 degrees rotation per each time step** is chosen for further V&V

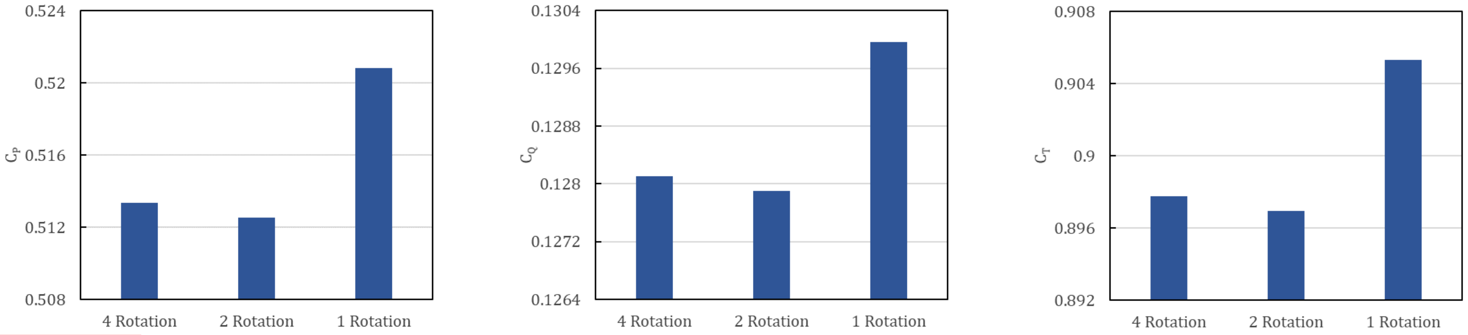
VERIFICATION AND UNCERTAINTY ANALYSIS

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



	r_k	ϵ_{21}	ϵ_{32}	R_k	Convergence	P_k	P_{kest}	P	δ	U_k
C_P	2	-8.0759E-04 (0.16%)	8.2925E-03 (-1.62%)	-9.7388E-02	Oscillatory Convergence	-	1	-	-	-
C_Q	2	-2.0152E-04 (0.16%)	2.0693E-03 (-1.62%)	-9.7388E-02	Oscillatory Convergence	-	1	-	-	-
C_T	2	-8.2208E-04 (0.09%)	8.3815E-03 (-0.93%)	-9.8082E-02	Oscillatory Convergence	-	1	-	-	-

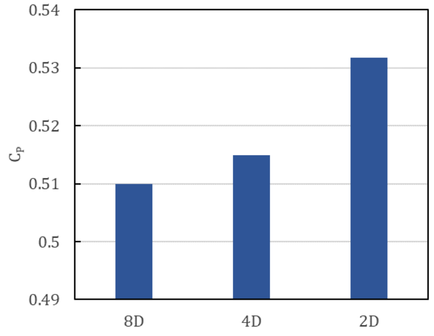


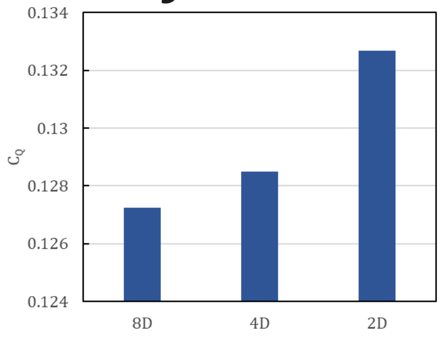
	r_k	ϵ_{21}	ϵ_{32}	R_k	Convergence	P_k	P_{kest}	P	δ	U_k
C_P	2	-8.3762E-04 (0.16%)	8.2842E-03 (-1.62%)	-1.0111E-01	Oscillatory Convergence	-	1	-	-	-
C_Q	2	-2.0902E-04 (0.16%)	2.0672E-03 (-1.62%)	-1.0111E-01	Oscillatory Convergence	-	1	-	-	-
C_T	2	-8.5244E-04 (0.09%)	8.3731E-03 (-0.93%)	-1.0181E-01	Oscillatory Convergence	-	1	-	-	-

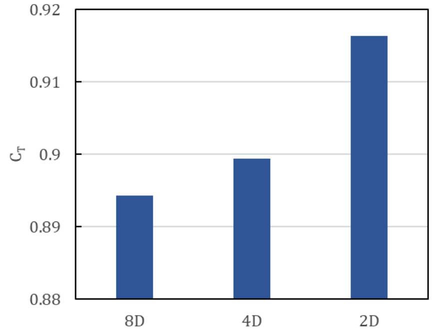
Number of free near wake panels corresponding to **the large of 1D or 2 rotations** is chosen

VERIFICATION AND UNCERTAINTY ANALYSIS

Number of Near Wake Panels Dependency

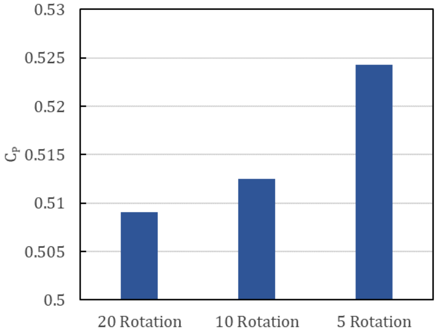


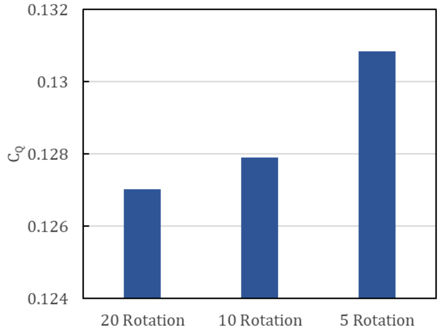


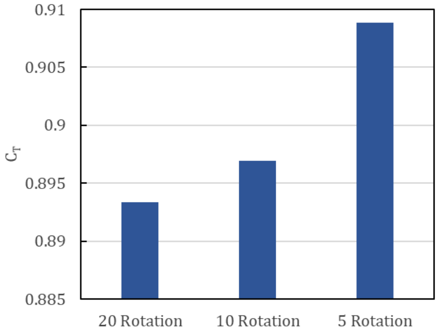


ϵ: Error between solutions
R_k: Convergence ratio
r_k: Refinement ratio
P_k: Order of accuracy
P_{kest}: Theoretical order of accuracy
δ: Error from Richardson Extrapolation
U_k: Uncertainty

	r_k	ϵ_{21}	ϵ_{32}	R_k	Convergence	P_k	P_{kest}	P	δ	U_k
C_P	2	5.0098E-03 (-0.98%)	1.6770E-02 (-3.26%)	2.9874E-01	Monotonic Convergence	1.7430	1	1.7430	2.1342E-03	0.5952%
C_Q	2	1.2501E-03 (-0.98%)	4.1847E-03 (-3.26%)	2.9874E-01	Monotonic Convergence	1.7430	1	1.7430	5.3256E-04	0.1485%
C_T	2	5.1050E-03 (-0.57%)	1.6921E-02 (-1.88%)	3.0170E-01	Monotonic Convergence	1.7288	1	1.7288	2.2056E-03	0.610%





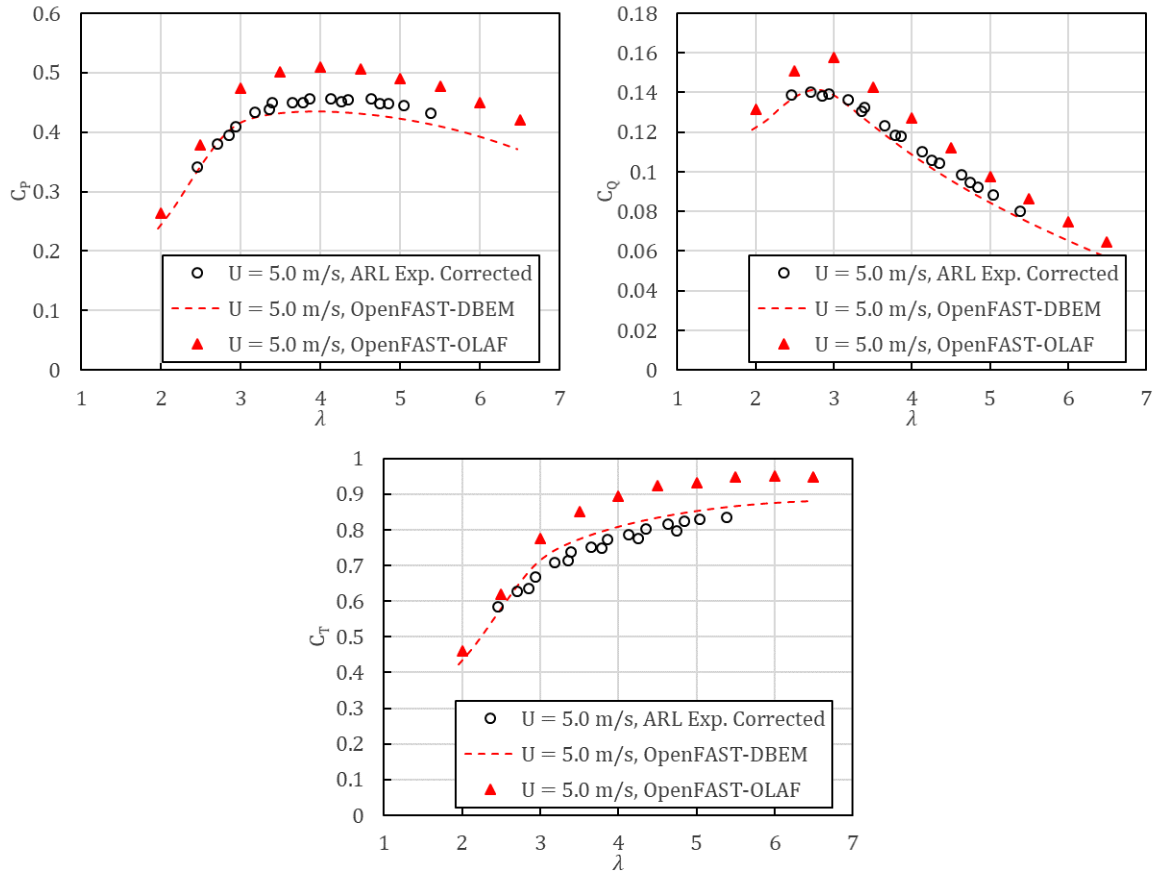


	r_k	ϵ_{21}	ϵ_{32}	R_k	Convergence	P_k	P_{kest}	P	δ	U_k
C_P	2	3.5091E-03 (-0.69%)	1.1754E-02 (-2.29%)	2.9853E-01	Monotonic Convergence	1.7440	1	1.7440	1.4934E-03	0.4167%
C_Q	2	8.7565E-04 (-0.69%)	2.9331E-03 (-2.29%)	2.9854E-01	Monotonic Convergence	1.7440	1	1.7440	3.7266E-04	0.1040%
C_T	2	3.5749E-03 (-0.40%)	1.1914E-02 (-1.33%)	3.0006E-01	Monotonic Convergence	1.7367	1	1.7367	1.5325E-03	0.426%

Number of near wake panels corresponding to **the large of 20D or 8 rotations** is chosen

VALIDATION

BEM vs FVW



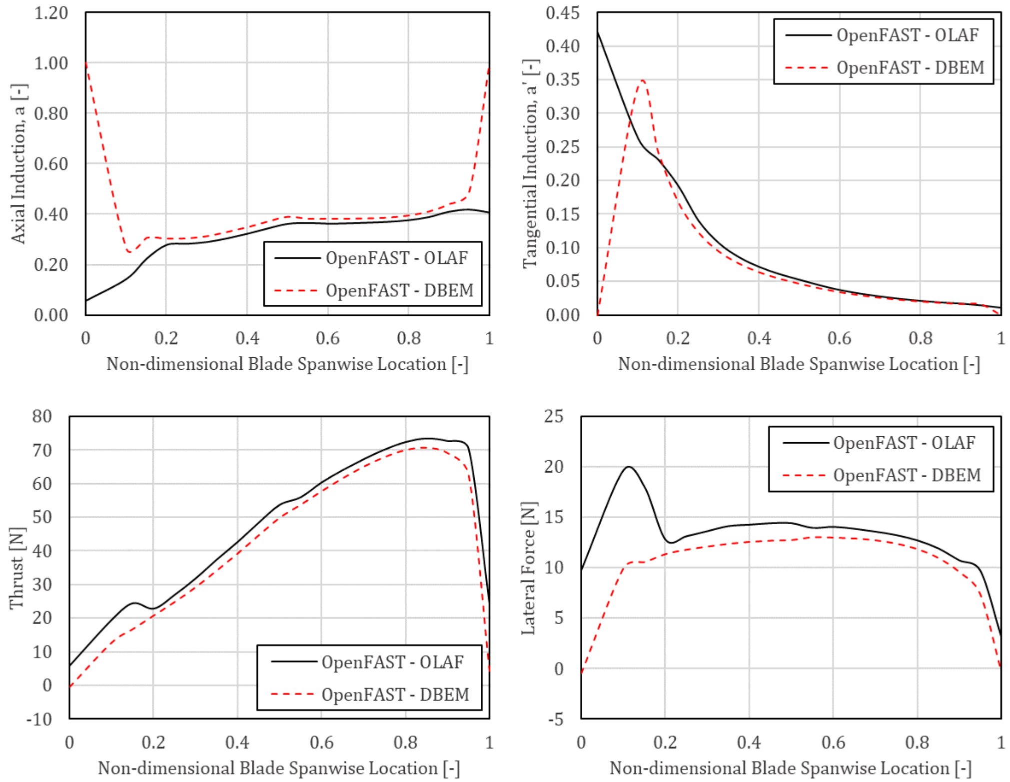
Turbine power, torque, and thrust coefficients curves estimated from the simulations using DBEM and FVW methods (red dashed line and red triangle, respectively) and blockage effect corrected measurement data (black empty circle)

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

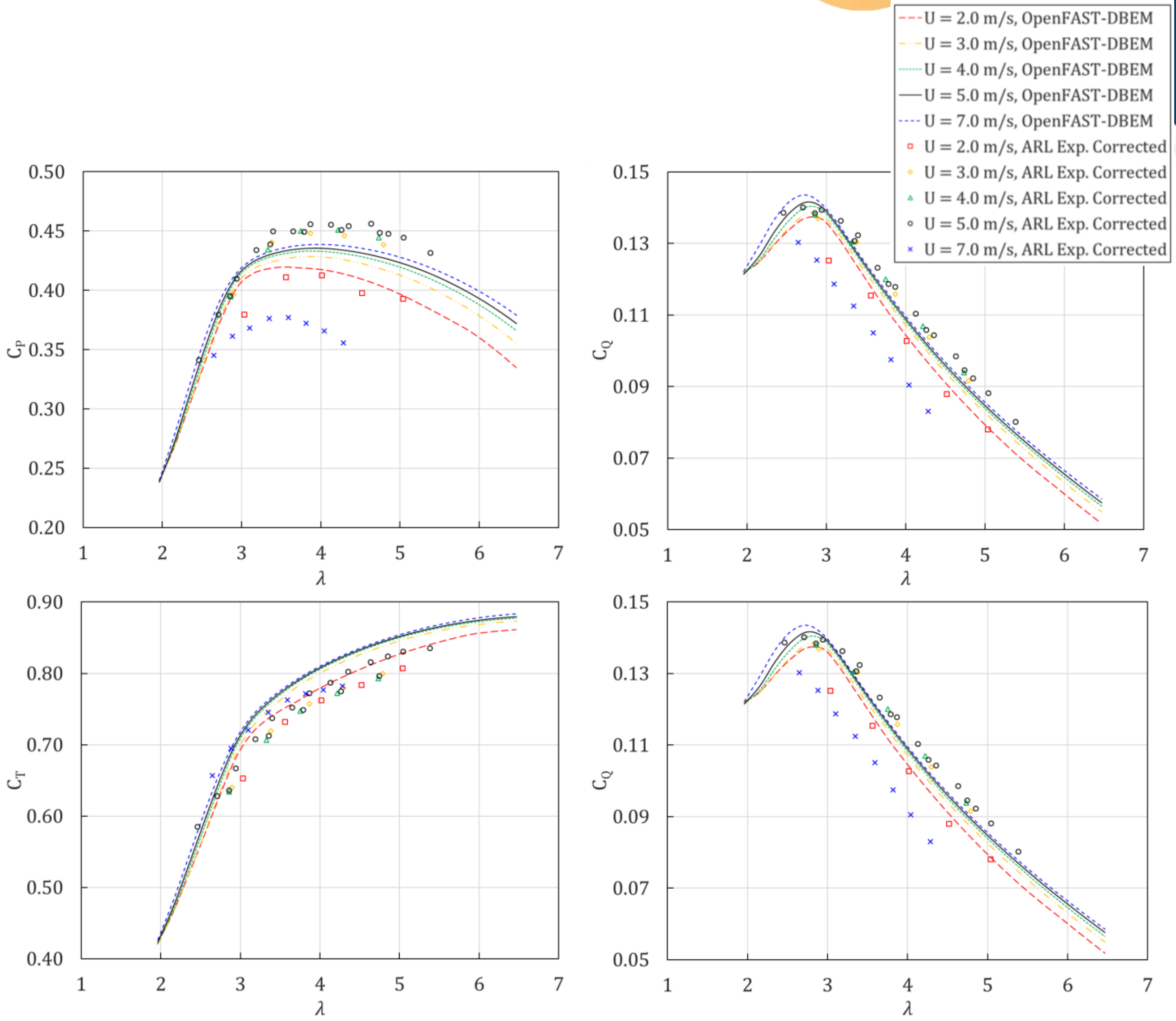


Local axial and tangential induction factors, and thrust and lateral forces acting on each blade segment along the blade spanwise direction at TSR of 4.0 estimated by FVW and BEM methods.

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

VALIDATION

Cavitation

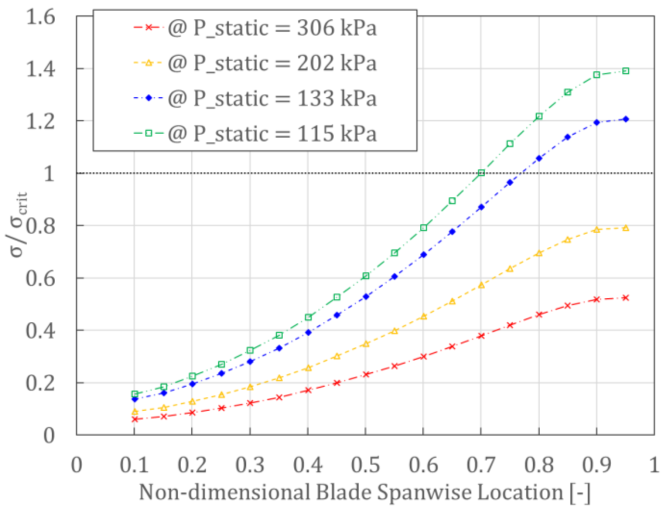
- Cavitation occurs when the local cavitation number is greater than or equal to the critical cavitation number
- Critical cavitation number is based on the minimum pressure coefficient of the blade section

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

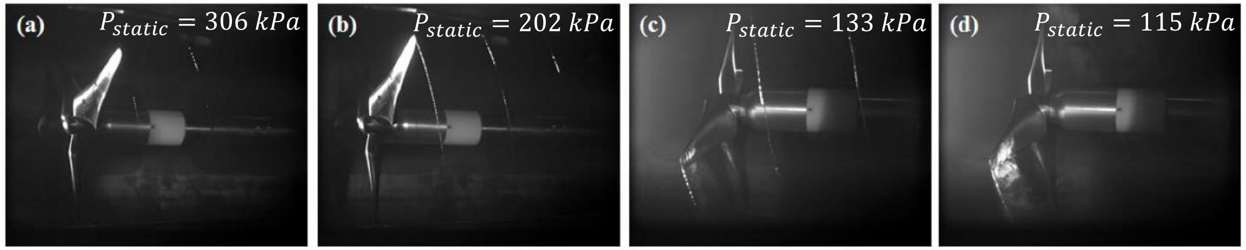
$$\sigma = \frac{(P_{atm} + \rho g h) - P_{Local}}{\frac{1}{2}\rho V_{rel}^2} = -C_{P,min}$$

- 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)

CONCLUSIONS

- **Addressed the limitations of XFOIL** in obtaining foil polar data for thick flatback geometries and at low Reynolds numbers.
- **Assessed dependency of the FVW model** on time step size and the number of panels considering rotating angle per time step, rotor diameter, and number of rotation.
- **Demonstrated that the OpenFAST BEM and FVW models can predict acceptable power performance and cavitation**. While not perfect, they are adequate for rotor design, analysis and performance assessment.

Future work

- Investigation on the effect of separation, dynamic stall, and boundary layer transition on hydrodynamic coefficients using a high-fidelity CFD model
- Verification on numerical methods for panelling, circulation solving, integration and their parameters
- More comprehensive model validation, including comparison of blade-load response, tower load, and wake velocity profiles

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