Tidal Turbine Benchmarking Project: Stage II – Head Waves

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31st October 2025

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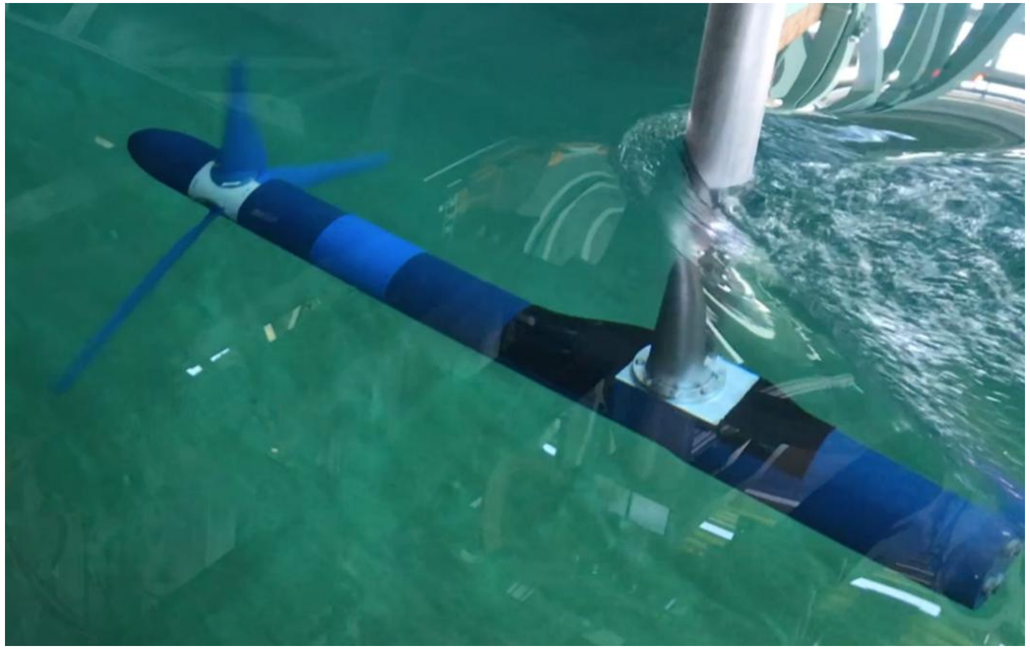
Benchmarking Project: Overview and Objectives

Unsteady loading and the inability to confidently predict unsteady loading and to quantify errors drives unnecessary redundancy and design conservatism.

- **Objectives**:
    1. improve accuracy of modelling techniques,
    2. improve confidence in the use of modelling techniques,
    3. quantify modelling errors for different techniques under different loading scenarios,
    4. development of novel measurement techniques.
- **Approach**:
    1. conduct a large laboratory test of a highly instrumented tidal turbine in waves and turbulent currents to provide underlying data,
    2. conduct a series of community wide (academia and industry) blind prediction exercises with staged data release, leading to open access datasets.



Requirements, Tests & Facility

Test requirements:

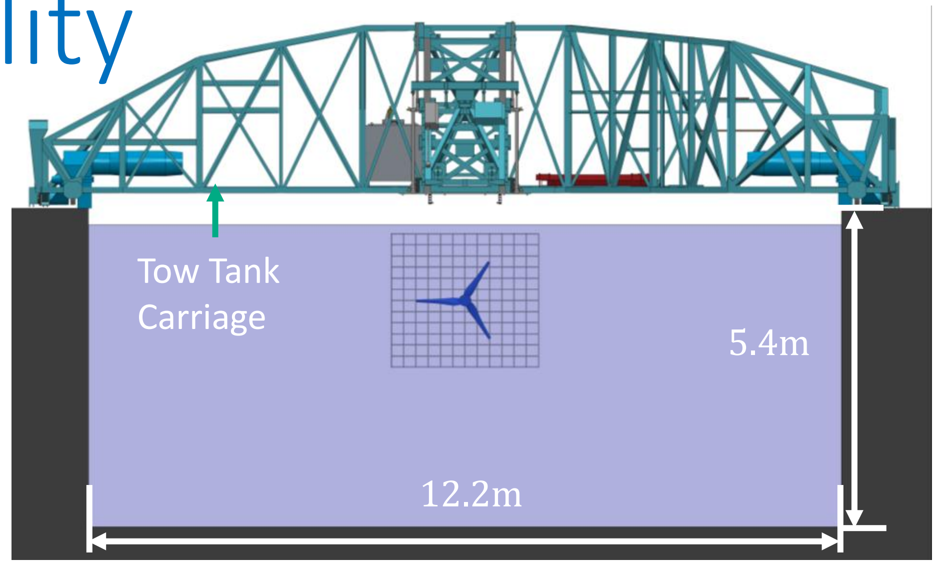
- Require **low blockage** experiments with a **large diameter** rotor for **in-blade sensing** and **Reynolds independence,**
- Flume options – blockage too high,
- Tow tank – low blockage but turbulence low,
- Solution: **tow tank with an upstream turbulence grid**

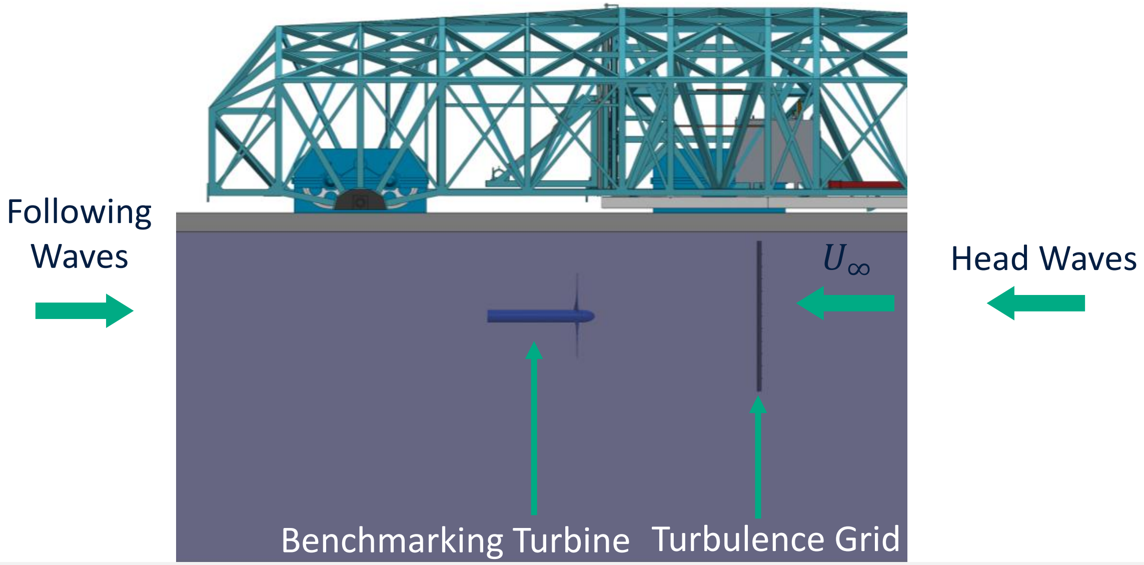
Test conditions:

- Stage 1: Uniform flow
  Uniform flow + Grid generated turbulence
- Stage 2a: Uniform flow + Head Waves
  Yawed uniform flow
- Stage 2b: Uniform flow + Following Waves

QinetiQ towing tank facility, Haslar, Portsmouth UK

- 270m (L) x 12.2m (W) x 5.4m (D)
- Tow speed 1m/s
- Tow length approx. 150m, settling time ~15mins.





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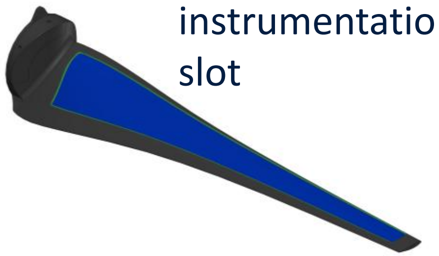
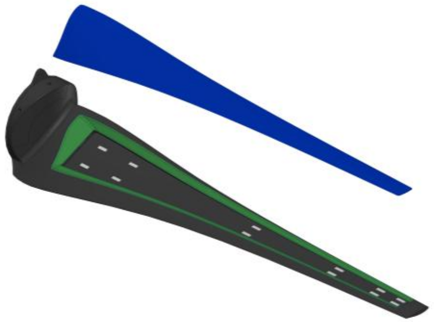
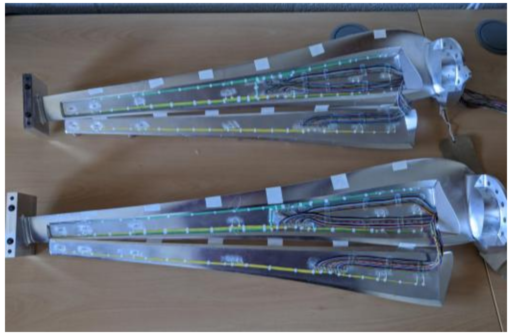
Instrumented Turbine

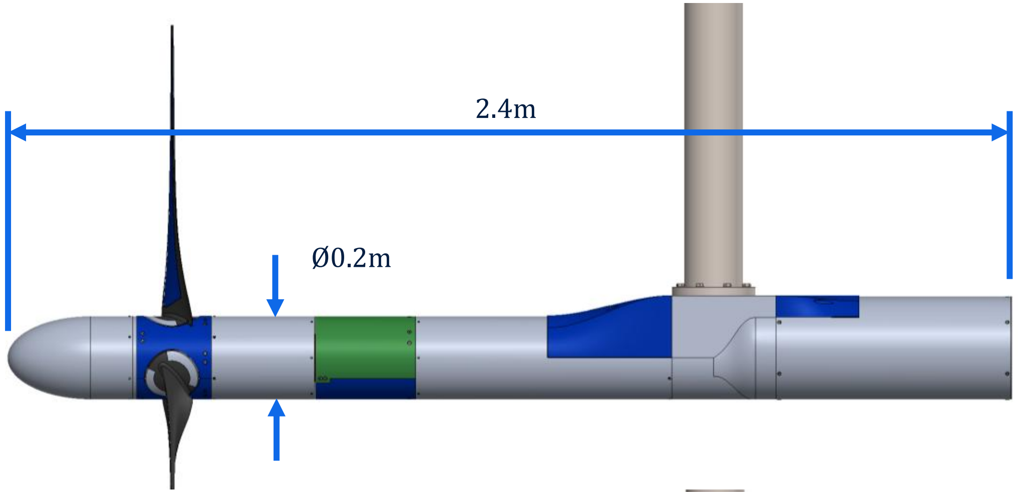
- 1.6m diameter rotor / 0.2m diameter nacelle
- Two blades instrumented with strain gauges at six radial locations for flapwise and edgewise bending moments
- Remaining blade instrumented with fibre Bragg sensors
- Individual root blade moments measured with hub – integrated root bending sensors
- Torque and Thrust measured by shaft mounted transducer upstream of front bearing

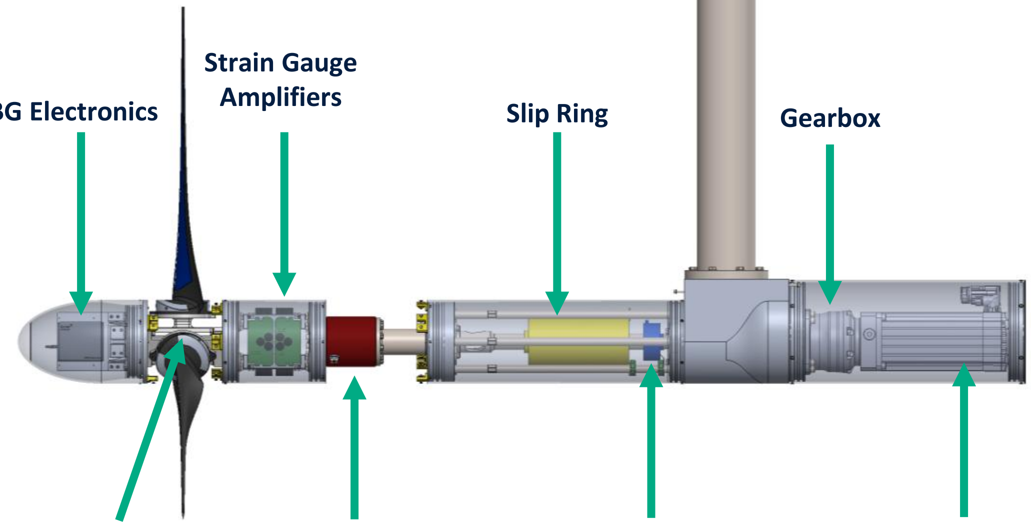


In-blade instrumentation slot









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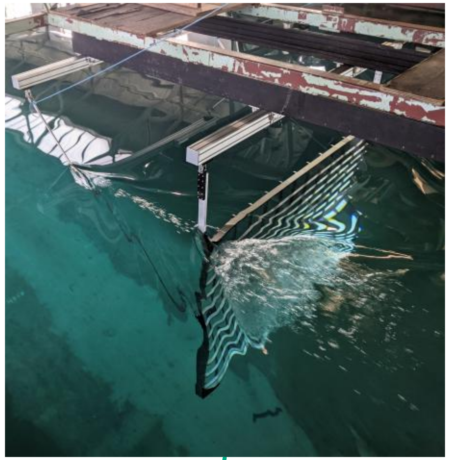
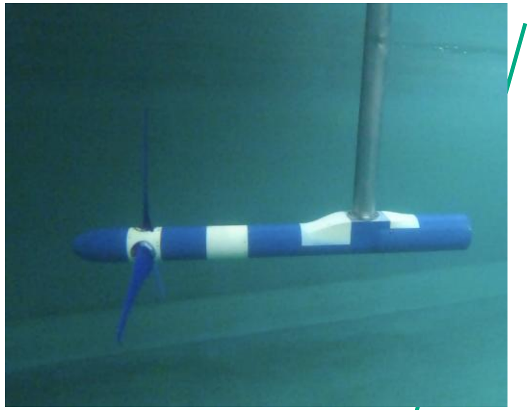
Timeline



15th ewtec 2023
European Wave and Tidal Energy Conference Series
BILBAO
3rd -7th SEPTEMBER 2023

16th ewtec 2025
European Wave and Tidal Energy Conference Series
MADEIRA
7th - 11th SEPTEMBER 2025



Turbulence Grid and wave characterisation Experiment
July 2021

April 2022
Benchmarking Turbine Experiment

Workshop I: Modelling Kick-off
June 2022

Stage 1 Analysis Submission Deadline
5th September 2022

2nd November 2022
Workshop II: Stage 1 Data Presentation

Workshop III: Stage 1 Round Up
17th January 2023

EWTEC September 2023
Workshop IV: Stage 1 – prediction review. Stage 2 – Release of first set of Wave Conditions

Follow on Wave & Yaw experiments
March 2025

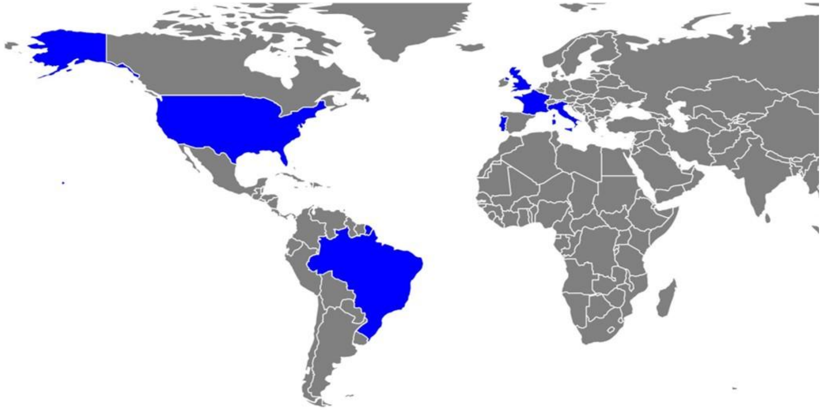
Stage 2 Wave Conditions specification
15th April 2025

EWTEC September 2025
Workshop V: Stage 2 Data Discussion

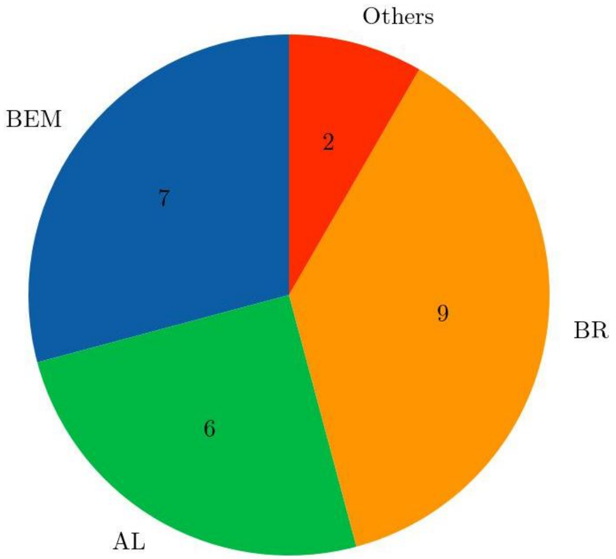
Stage 2 Analysis Submission Deadline
16th January 2026

Stage 1: Benchmarking Participants

- 12 collaborating research groups:
  - from across academia and industry
  - from 6 countries; UK, France, Italy, Portugal Brazil & USA.



- 26 submissions from a wide range of methods falling into 5 categories:
  - Blade Element Momentum (BEM)
  - Blade Resolved CFD (BR)
  - Actuator Line CFD (AL)
  - Boundary Integral Equation Model (BIEM)
  - Vortex methods



Benchmarking cases

Low Turbulence (LT) Cases													
Case No.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
U_∞ [m/s]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
λ	4.02	4.52	5.03	5.36	5.53	5.78	6.03	6.53	6.70	7.04	7.20	7.54	7.87

Elevated Turbulence (ET) Cases											
Case No.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
U_∞ [m/s]	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207
λ	3.91	4.46	4.91	5.37	5.64	5.82	6.19	6.37	6.92	7.37	7.73

- Participants asked to concentrate on priority (yellow) cases.
- LT cases submitted by 24 participants, ET cases submitted by 18 participants.

Participants: *Blade Resolved*

Submission	Solver	Turbulence Model	State	Wall Treatment	Mesh Size	Flow Domain	Free Surface
blueOASIS-BR-RANS	ReFRESCO 2.8.0	k-ω SST	Steady	Resolving	34.3M	MRF * WR §	None
CHE-BR-uRANS	STAR-CCM+	k-ω SST	Unsteady	Resolving	3.5M	TTG †	VOF ‡
CNR-INM-BR-uRANS	X NAVIS (in-house)	SA	Unsteady	Resolving	24M	MRF WR	None
LOMC-BR-RANS	OpenFOAM	$k - \omega$ SST	Steady	Resolving	26M	MRF	None
NREL-BR-RANS	STAR-CCM+	$k - \omega$ SST	Steady	Function	4.23M	MRF	None
NREL-BR-uRANS	STAR-CCM+	$k - \omega$ SST	Unsteady	Function	21.15M	TTG	VOF
UoE-BR-RANS	OpenFOAM	$k - \omega$ SST	Steady	Resolving	18.8M	MRF	None
UoO-BR-RANS	OpenFOAM	$k - \omega$ SST	Steady	Resolving	38M	MRF	None
USP-BR-DES	OpenFOAM	DES SST	Unsteady	Function	33.6M	TTG	None

* MRF = multiple reference frame technique with by default a 120° cylindrical wedge domain of a single blade, or if specified the § WR = whole rotor geometry. † TTG = tow-tank geometry with rotating turbine submerged at experimental depth. ‡ VOF = Volume-of-Fluid free surface representation.

Participants:
Actuator Line

Submission	Solver	Turbulence Model	Mesh Size	2D Polars	Polar Interpolation	Free Surface Rep.	Nacelle Model	Tip-loss Model
QUB-AL-LES	OpenFOAM	LES Smagorinsky	16.3M	Provided *	Single polar	VOF §	None	SM ‡
UoM-AL-uRANS	STREAM (in-house)	k-ω SST	0.94M	Provided	Single polar	NDFS §	IB †	None
UoM-AL-LES	DOFAS (in-house)	LES WALE	30M	Provided	Single polar	NDFS	IB	SM
UoO-AL-NRSM	OpenFOAM	k-ω SST	6.91M	Provided	Tu Interpolation	NDFS	Resolved	SM
UoO-AL-NRWM	OpenFOAM	k-ω SST	6.91M	Provided	Tu Interpolated	NDFS	Resolved	WM
UoO-AL-IBWM	OpenFOAM	k-ω SST	10.80M	Provided	Tu Interpolated	NDFS	IB	WM ‡

*2D performance polars provided as part of the benchmarking exercise (from 2D RANS). § VOF = Volume of Fluid deform-able free surface, NDFS = Non-Deformable Free Surface. † IB = Immersed Boundary method. ‡ SM & WM = Shen et al.- and Wimshurst & Willden-type tip-loss models.

Participants:
Blade Element Momentum

Submission	2D Polars	Polar Interpolation	Turbulent Inflow	Induction/Wake Correction	Root Model	Tip-loss Correction
LOMC-BEM	2D RANS	Re-Tu Interpolation	None	Modified Turbulent Wake Model	None	PDL †
NREL-BEM	Provided * with Rotation Correction	Single polar	None	Buhl Model	PDL	PDL
SU-BEM	Provided	Single polar	Sandia Method	High-induction Model	PDL	PDL
UoE-BEM	XFOIL	Re Interpolation	Spectral Method	Buhl Model	GLT ‡	GLT
UFU-BEM-Aerodas	Provided with Aerodas Correction	Single polar	None	None	PDL	PDL
UFU-BEM-SD	Provided with Stall Delay Correction	Single polar	None	None	PDL	PDL
UoM-BEM-1	Provided	Single polar	None	GLT	None	GLT
UoM-BEM-2	Provided	Single polar	Import from LES	GLT	GLT	GLT

* 2D performance polars provided as part of the benchmarking exercise (from 2D RANS). † PDL = Prandtl-type hub / tip correction.

‡ GLT = Glauert-type induction / hub / tip correction.

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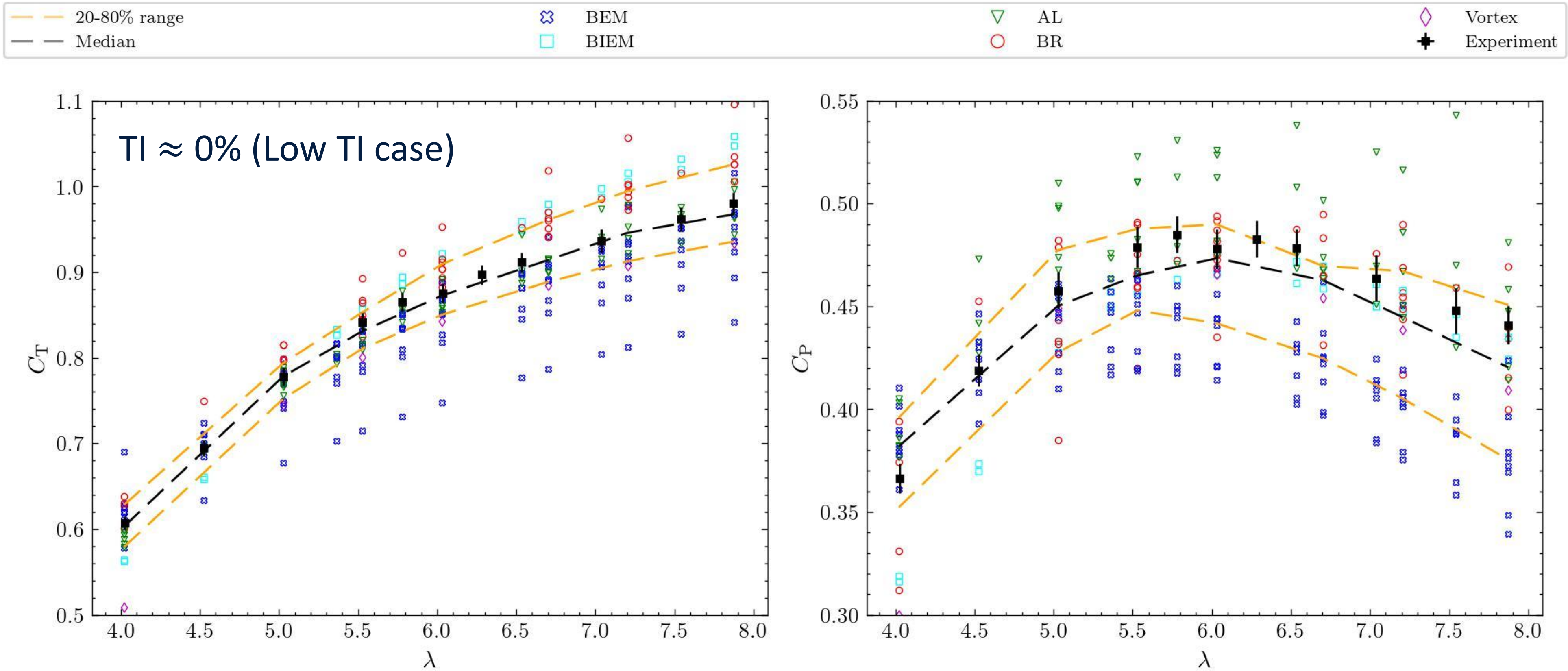
Other Participants:

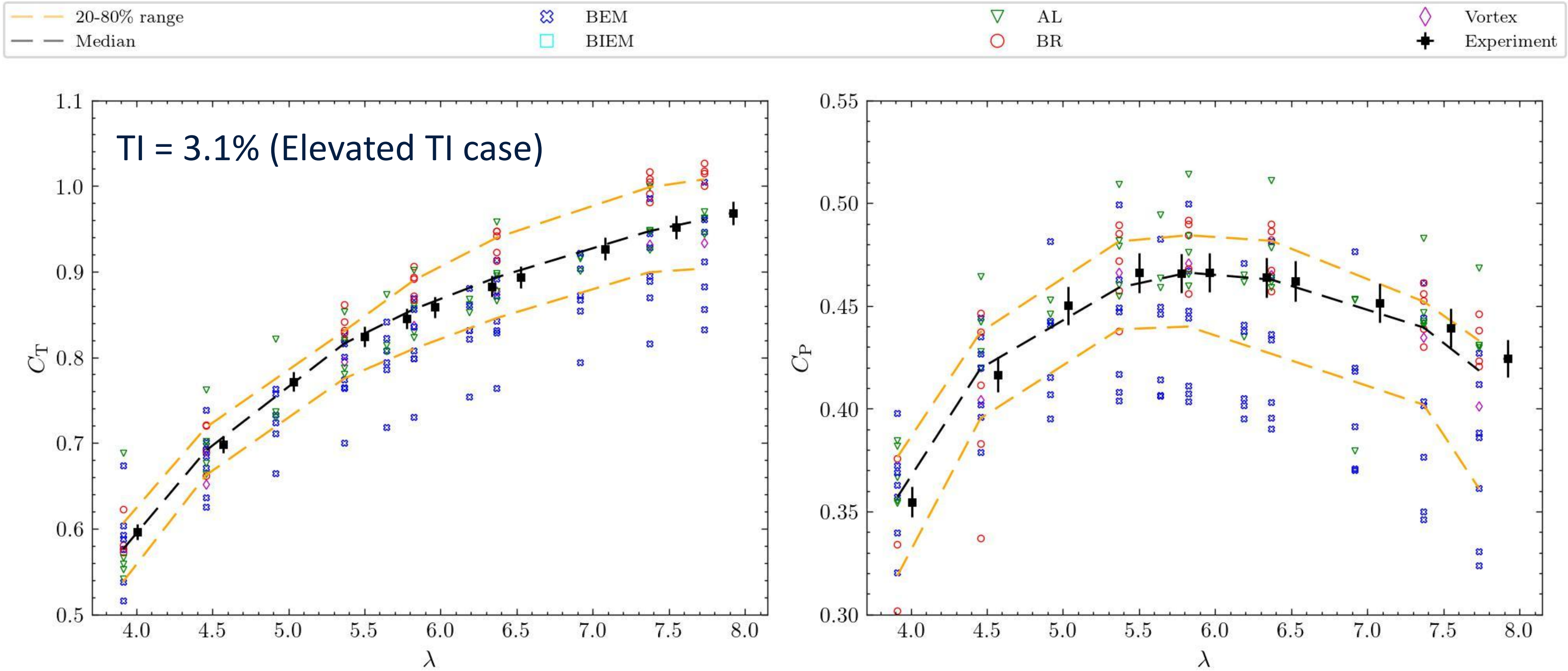
Submission	Method Type	Description
CNR-INM-BIEM-D12 / D22	BIEM	Boundary Integral Equation Model. Uses a Viscous Flow Correction model to estimate the effects of viscosity on blade loads with input 2D flow lift and drag curves calculated using XFOIL. D12 / D22 refers to alternative shape parameters used in modelling the curvature of the wake surface in the tip vortex region.
LOMC-Vortex	BR	3D unsteady Lagrangian Vortex Particle Method. Blades represented by lifting line model using tabulated 2D lift and drag coefficients.

Blind prediction results



- Power and thrust coefficients are generally well predicted. 20-80% prediction interval particularly good,
- 20-80% Thrust predictions are more tightly banded ($\pm 5\%$) than Power ($+7\% \rightarrow -11\%$),
- AL, BEM, BR, BIEM, Vortex, exhibit different biases, with results spread often linked to choice of sub-models.

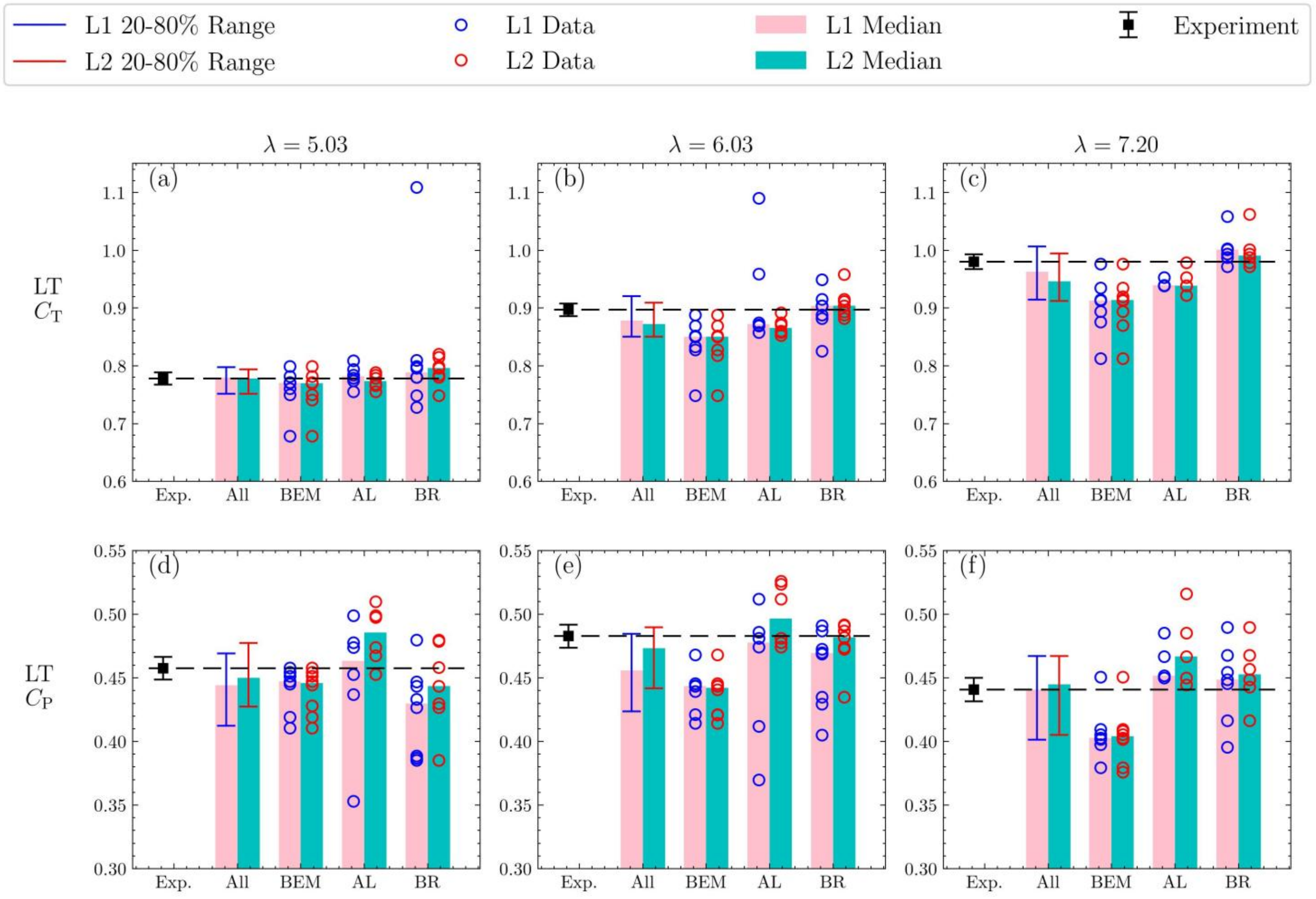
Blind prediction results



- BR tendency to underpredict C_P and overpredict C_T.
- BEM methods tend to underpredict both.
- BIEM over-predicts C_T but C_P good at high TSR.
- Vortex method consistently under-predicts LT cases, but more accurate for ET cases.
- AL methods good alignment in both C_P and C_T.

Reduction in Prediction Uncertainty

Figure: Medians and ranges of C_T and C_P for fully blind (L1) and user-error-corrected (L2) submissions, TI ~ 0% (LT case)



Definition of data submission levels

- **Level 1 (L1)** – completely blind submission
- **Level 2 (L2)** – "user-error corrected" submissions correction for data input, setup errors etc
- **Level 3 (L3)** – New results that use improved modelling techniques / approaches building on data comparisons from this and other exercises.

Improvements from **L1** *to* **L2** result from having a reliable dataset against which to verify model setup.

Table: Standard deviations of L1 and L2 solutions.

Low Turbulence (LT) Cases								
	C_T				C_P			
	All	BEM	AL	BR	All	BEM	AL	BR
L1	11.8	6.02	17.1	17.3	15.49	5.15	10.5	15.6
L2	5.45	5.86	2.58	4.80	6.93	4.96	1.64	3.88

Elevated Turbulence (ET) Cases								
	C_T				C_P			
	All	BEM	AL	BR	All	BEM	AL	BR
L1	14.7	7.71	2.26	22.8	16.5	6.55	1.54	22.3
L2	6.22	7.44	5.04	3.03	7.87	6.15	4.33	2.56

Reduction in Prediction Uncertainty

This has already **provided quantifiable improved confidence in simulation model application**.

Standard deviations of solutions reduced by over 50% from c. 15% at **L1** to 7% at **L2** for **All** cases (methods, TSRs, TIs, C_T and C_P).

Further improvements to accuracy (**L3**) being sought by modellers through improvements and refinements to modelling techniques using benchmarking data as reference data set.

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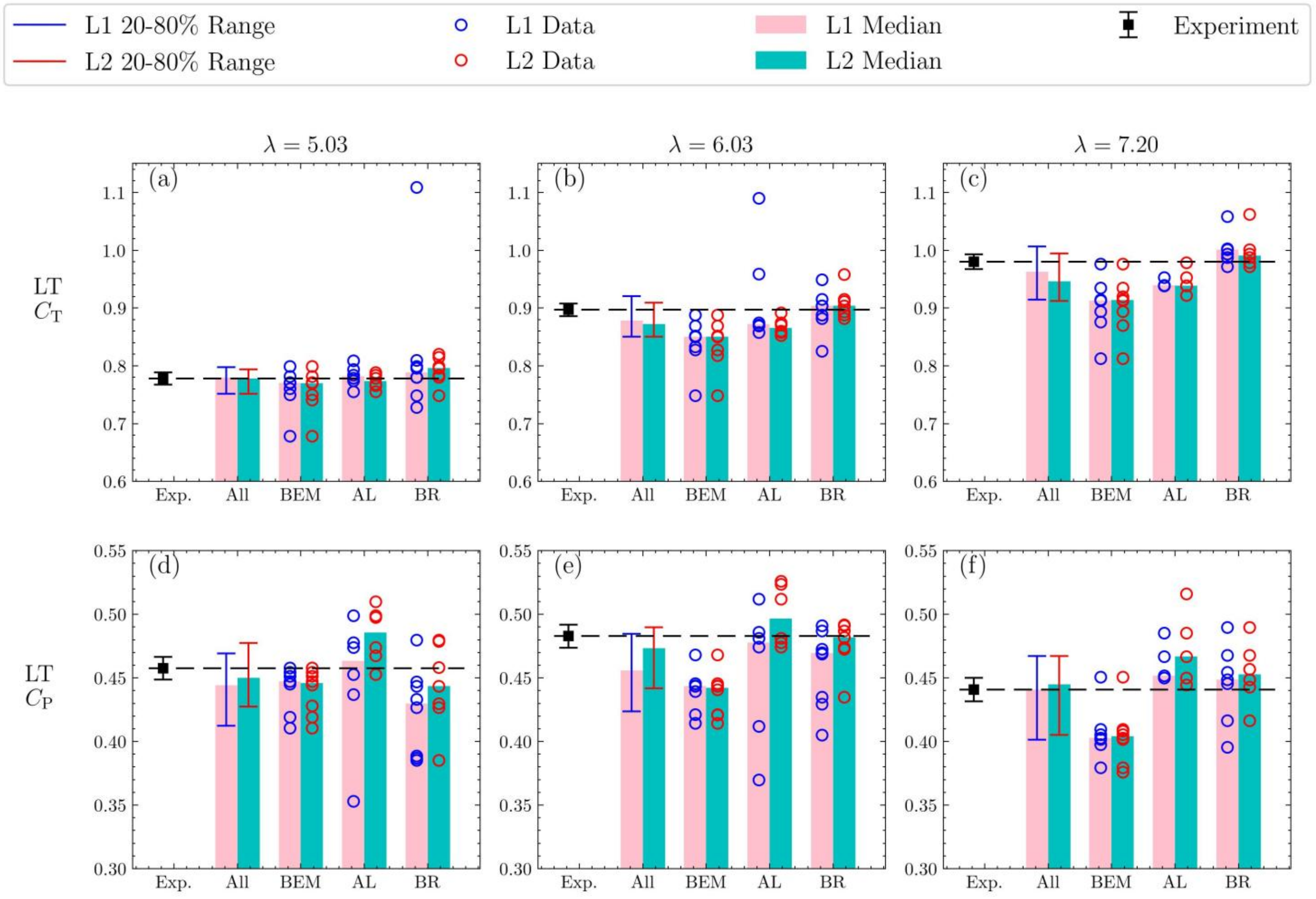
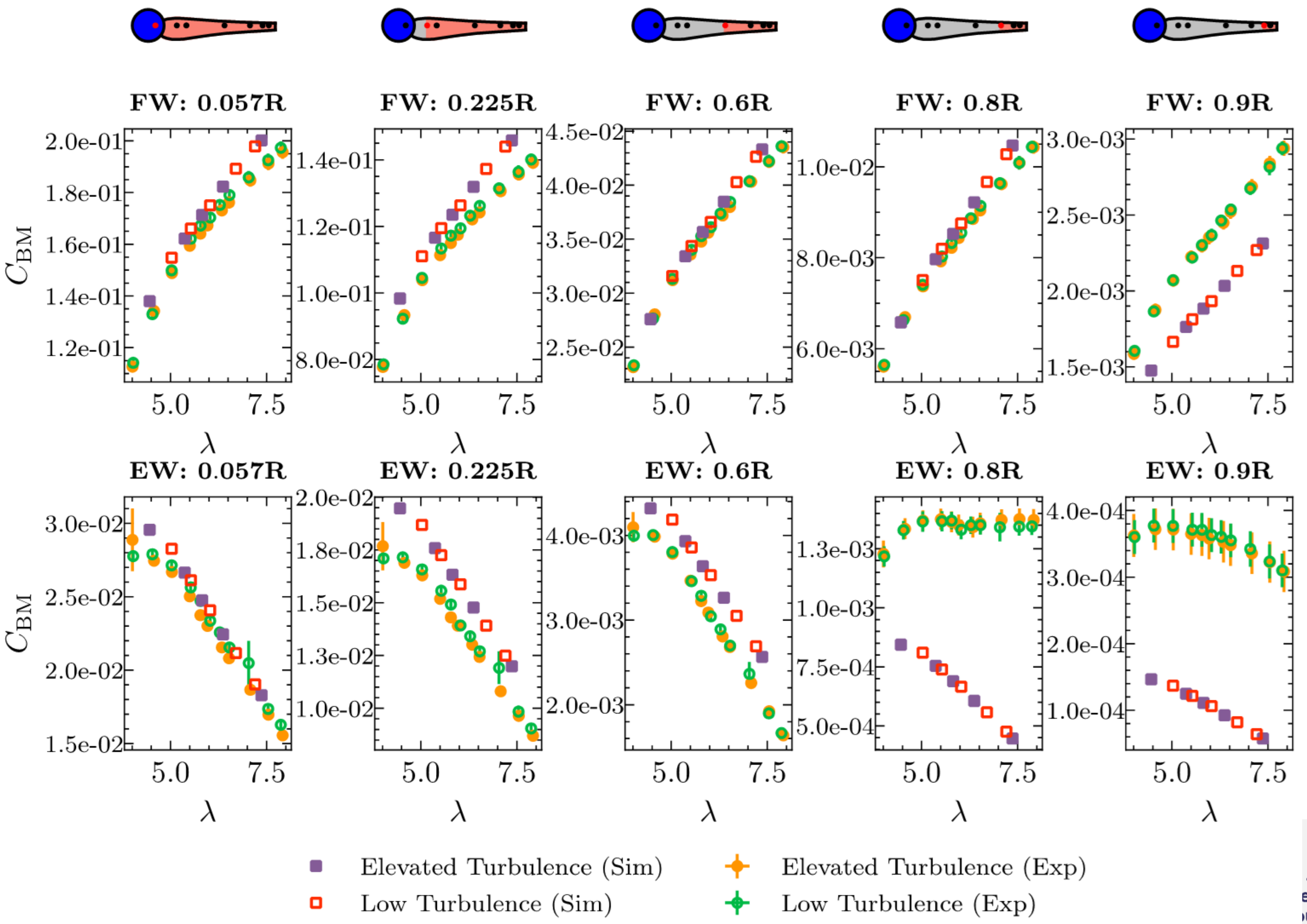


Bending Moments – Experiments & CFD

- Experimental data for spanwise distributed Flapwise (FW) and Edgewise (EW) BMs enables assessment of model performance at a more granular level.
- FW and EW bending moment coefficients

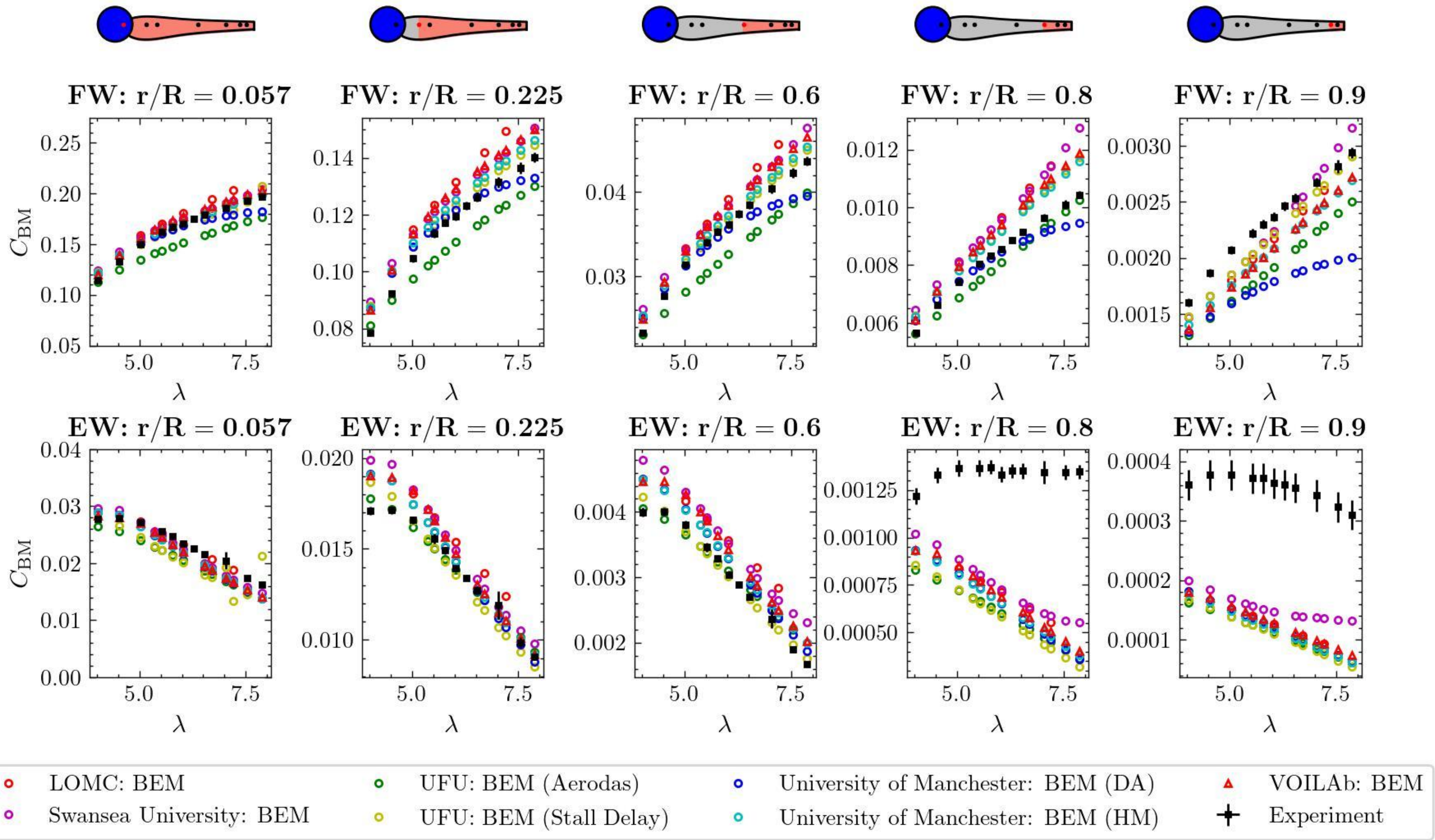
$$C_{BM} = M_{BM}\frac{16}{\rho \pi D^3 U_\infty^2}$$

- Minor changes between Low and Elevated TI levels,
- CFD simulations over-predict EW in mid-span locations & under-predict FW & EW at tip,
- CFD Root BM well predicted.



Bending Moments – BEM & BIEM

- BEM models tend to under-predict inboard bending moments, over-predict through midspan up to 0.8R (FW) and 0.6R (EW), and then under-predict further outboard.
- Divergence in model predictions outboard due to choice of tip correction & high thrust turbulent wake model.
- Over/under predictions lead to net under-prediction in C_T & C_P.



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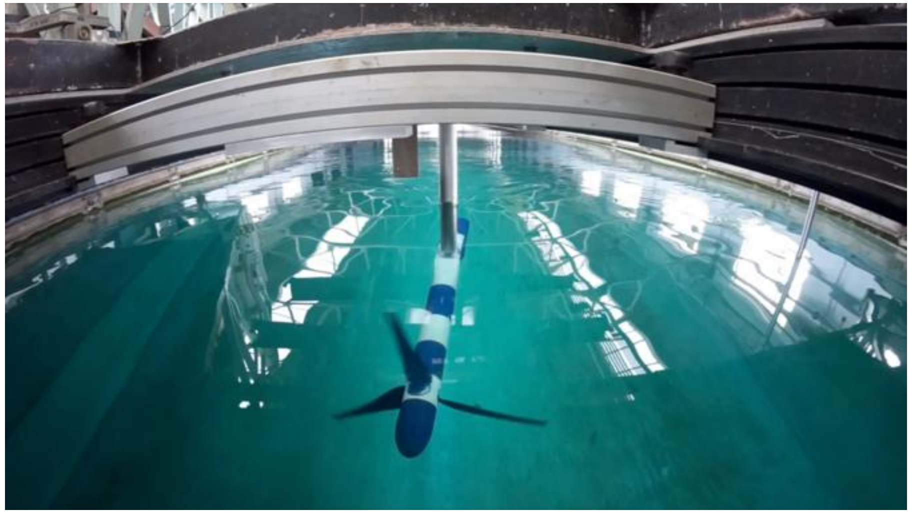
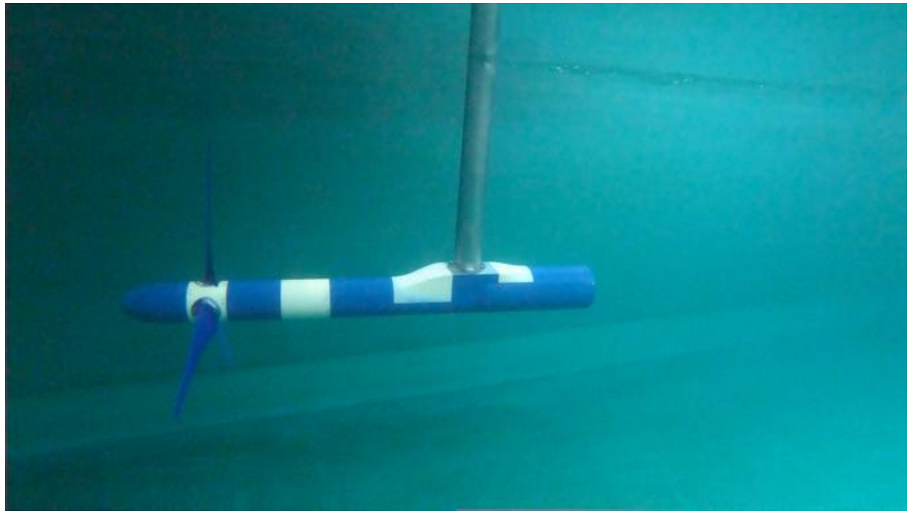
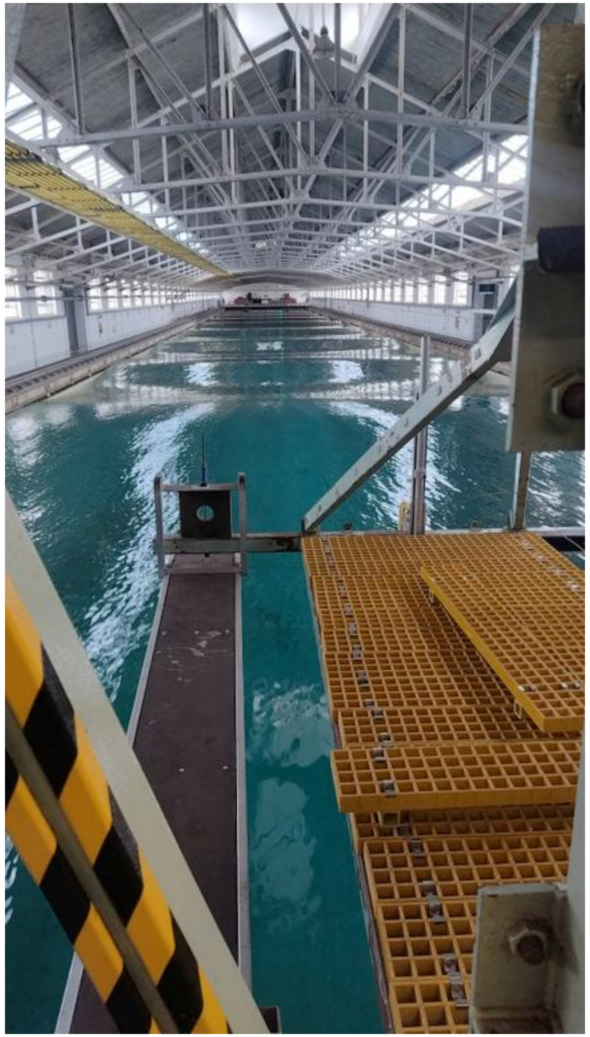
Stage 2: Experiments in waves

- Turbine tested at QinetiQ, March 3rd–21st & 6-24th October 2025
- Wave characterization using 3 different techniques – 7 solid gauges, 6 ultrasonic probes and a rake of “barnacle” 5-hole probes
- Wave experiments covering >**50 wave conditions**
- Additional steady flow **experiments with yawed turbine**
- Total of **> 400 tests** performed







Selection of Wave Conditions

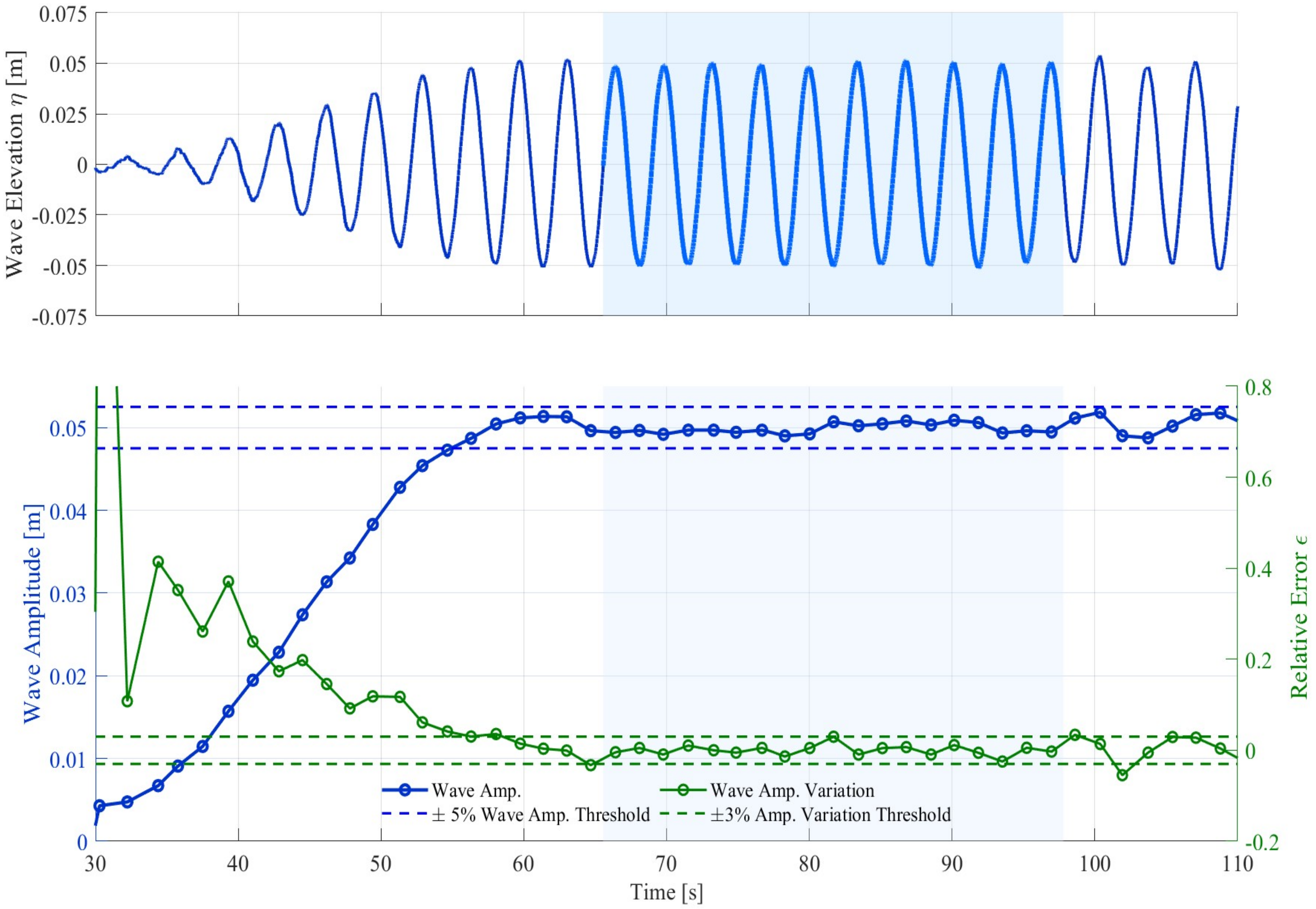
Wave stability criteria:

- <5% variation from the set amplitude
- <3% cycle to cycle amplitude fluctuation

Torque stability criteria:

- <7% cycle to cycle torque fluctuation

Selected cycles are combined with those from repeated tests conducted under similar conditions.



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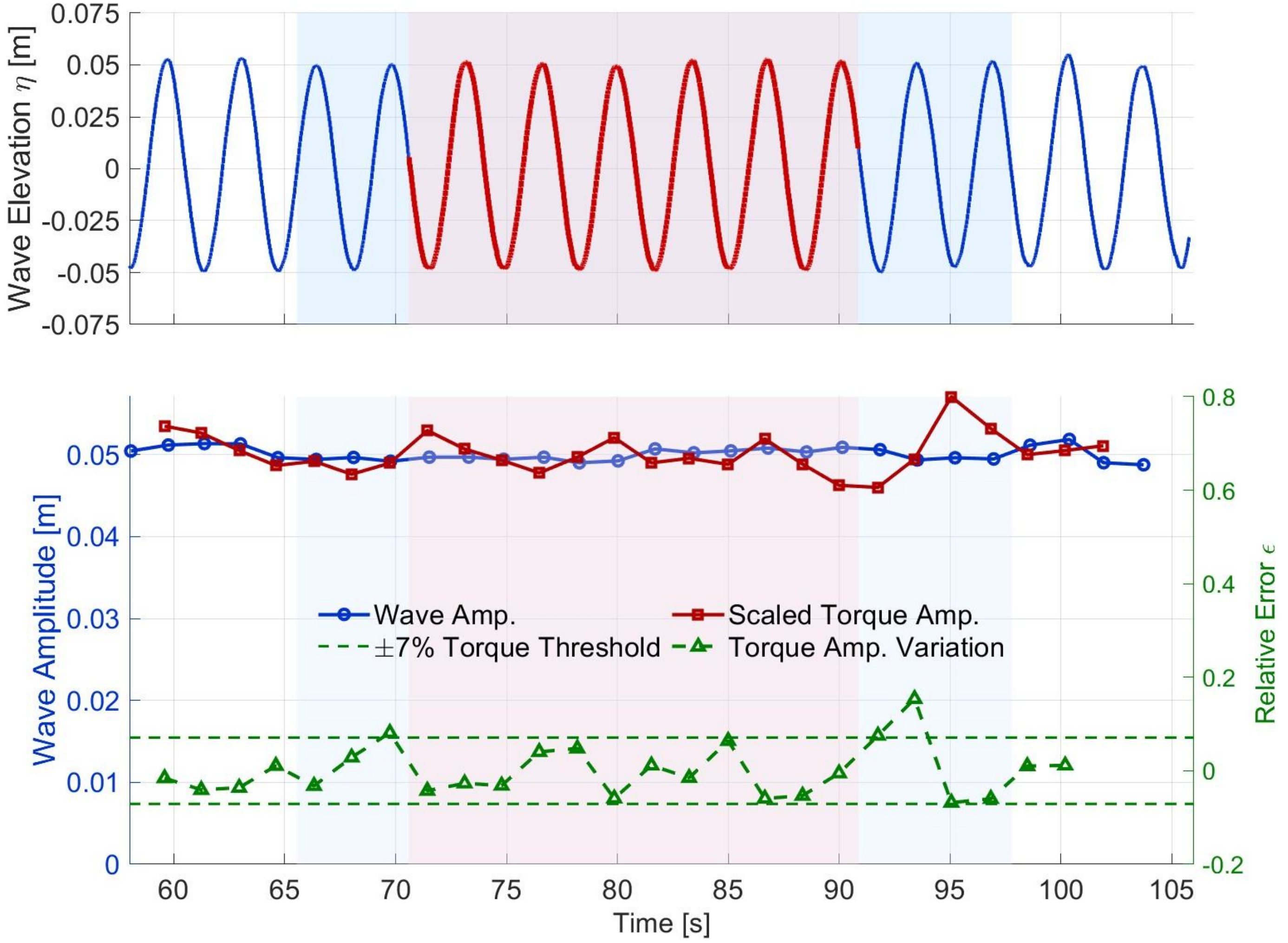
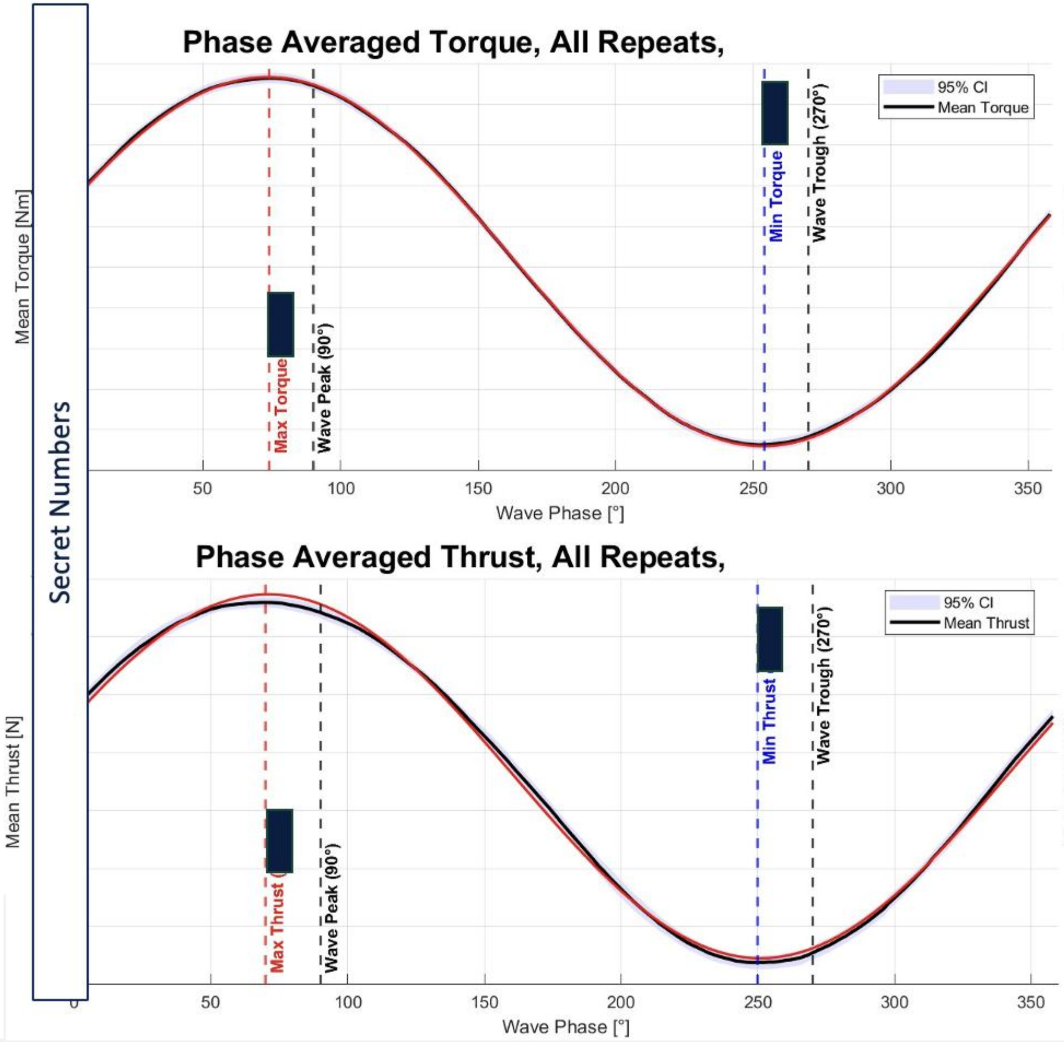
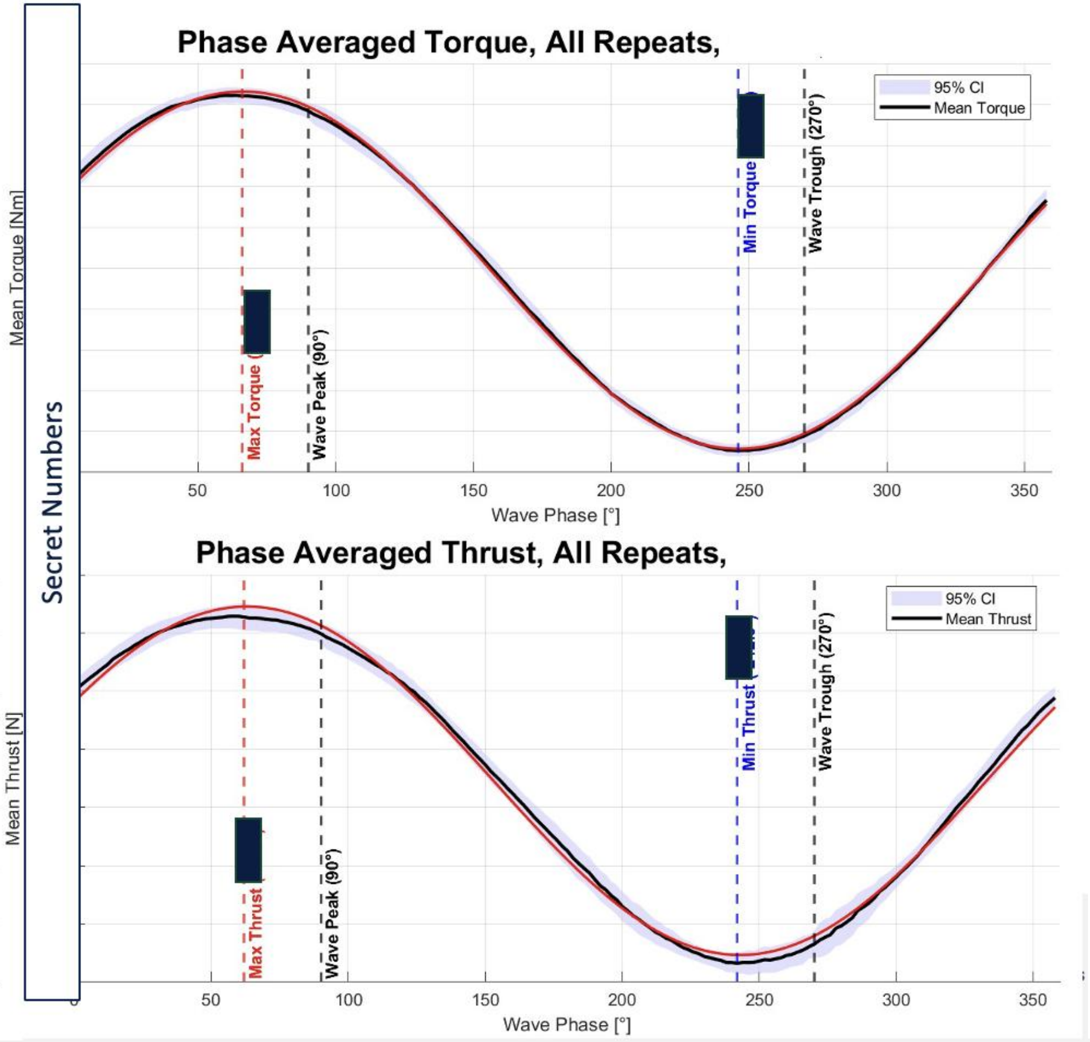
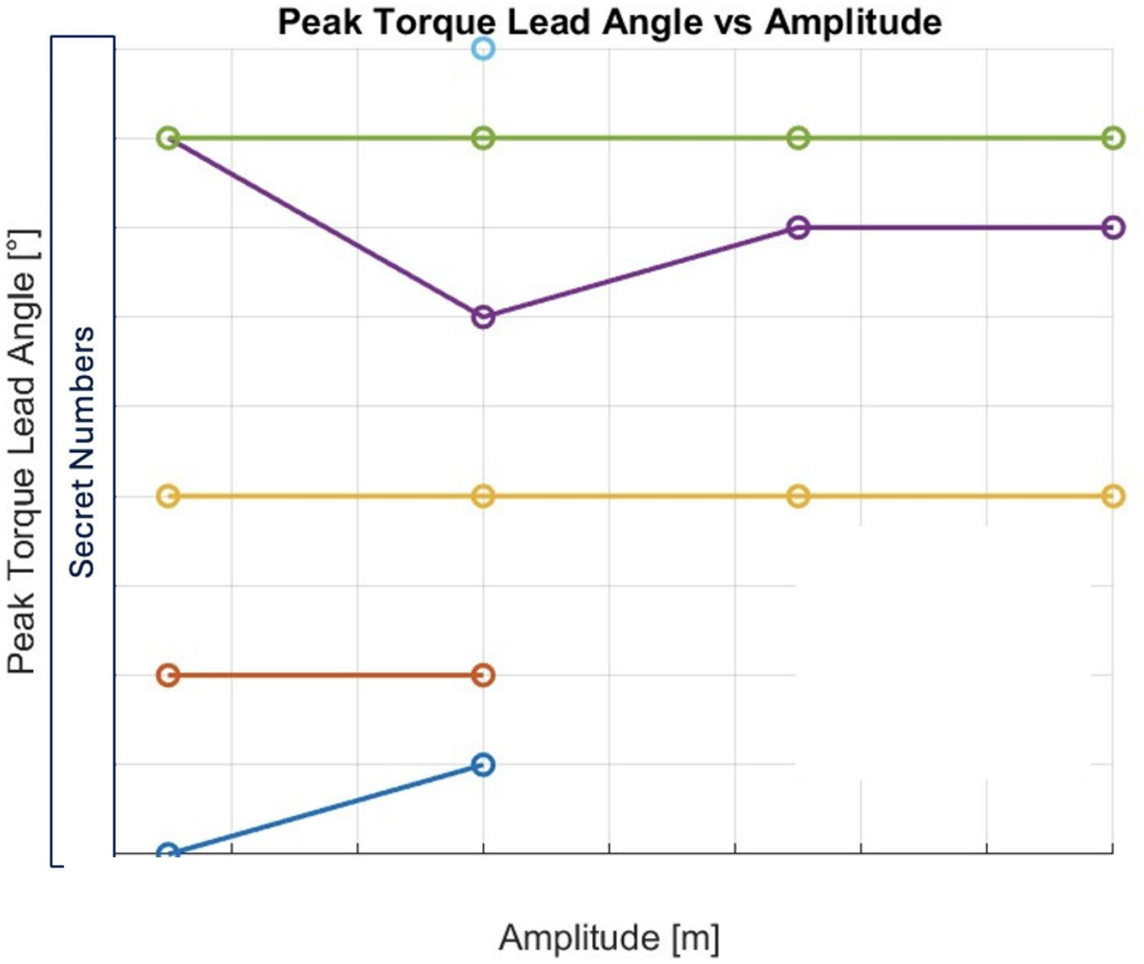


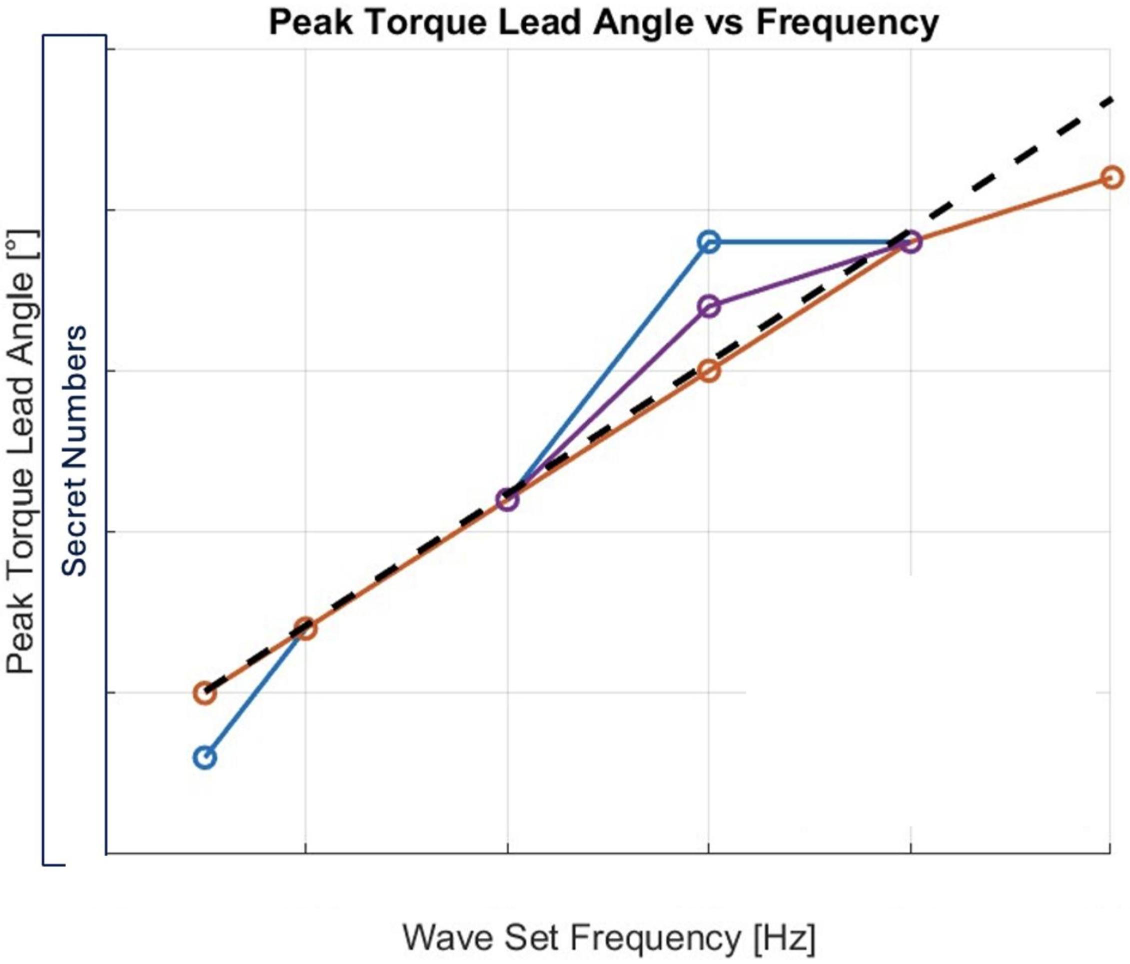
Phase-averaged results





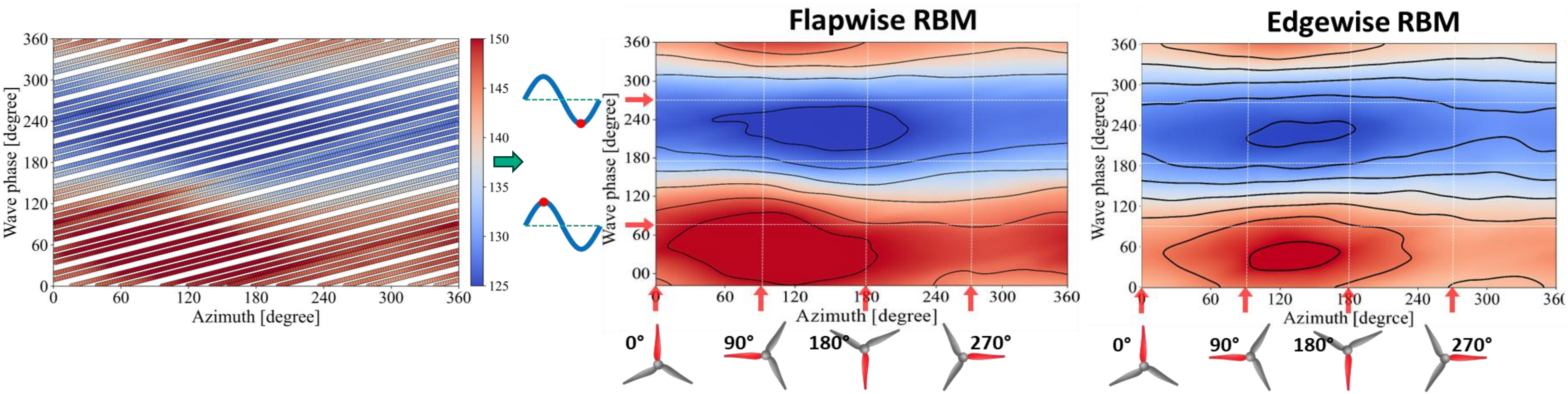
Torque phase lag





Unsteady loading in waves

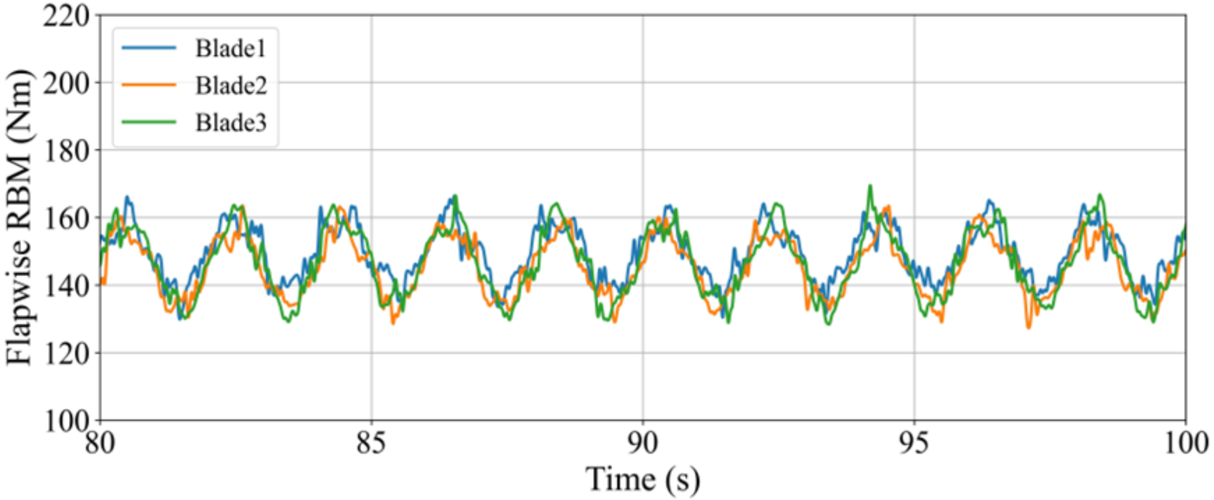
- RBMs from all 3 blades selected over stable wave cycles across all repeated tests,
- RBM data visualized in both wave phase and blade phase (azimuthal) coordinates,
- **Flapwise and edgewise load maxima / minima do not occur in phase with wave crest / trough and blade top / bottom dead centre positions,**
- **Hypothesis**: wave-induced perturbations correlated loads well along blade spans when blades near horizontal, but decorrelate loads when blades vertical due to depth decay.



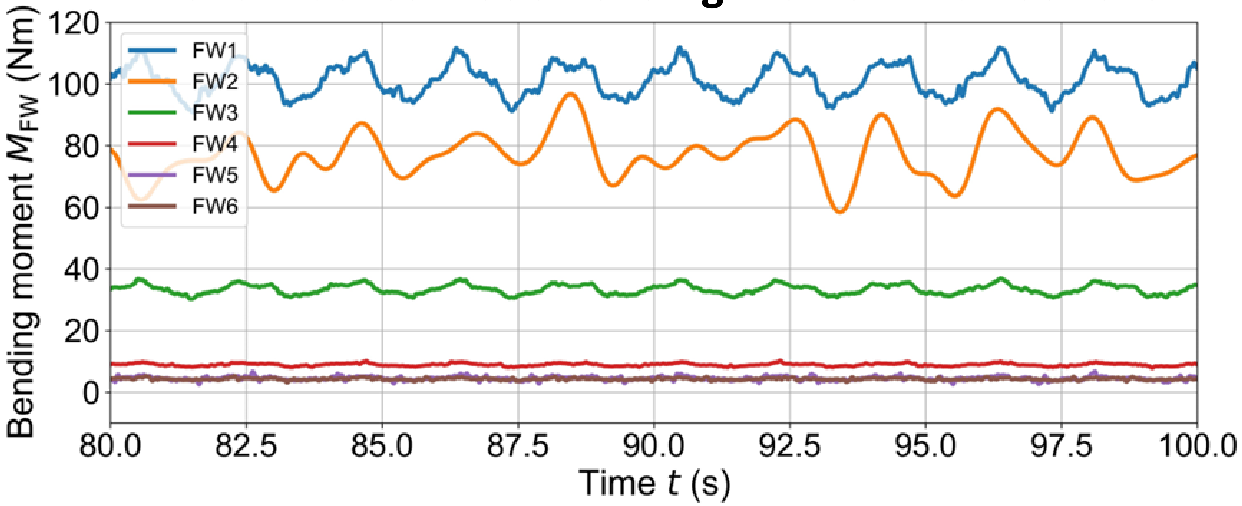
Unsteady loading in waves

- RBM and bending moments along span are analyzed to quantify unsteady blade loading
- Wave-induced unsteady load amplitudes can reach up to 30% of the steady-state blade load (at H/D=0.0625)

Wave-Induced RBM Fluctuations



Wave-Induced Blade Bending Moment Fluctuations



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How to Participate?

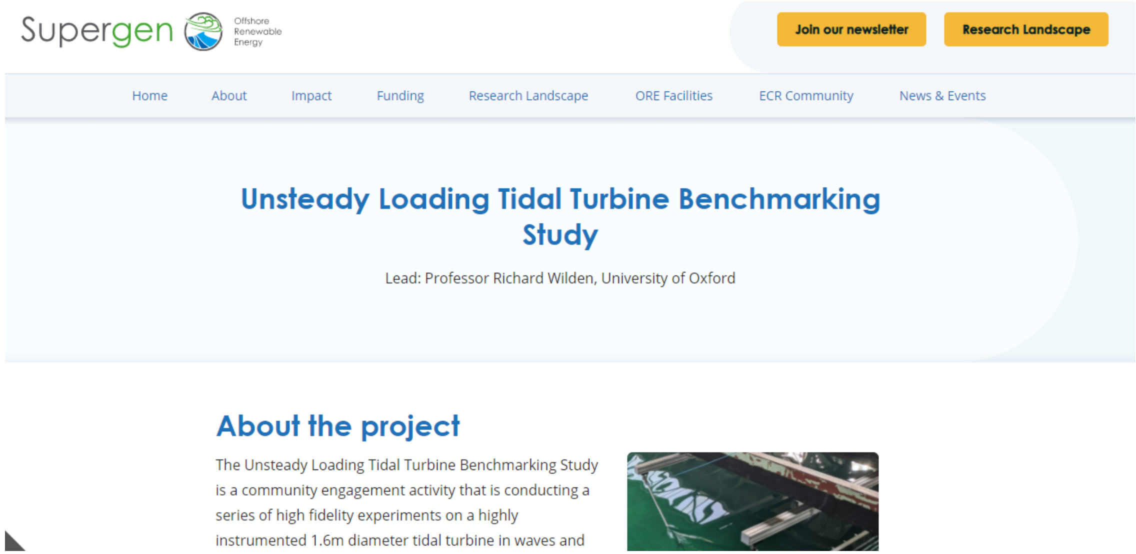
For further details on the Tidal Turbine Benchmarking Project, including benchmark data and how to take part:

https://supergen-ore.net/projects/tidal-turbine-benchmarking

Email Richard Willden Richard.Willden@eng.ox.ac.uk

or Xiaosheng Chen xiaosheng.chen@eng.ox.ac.uk

1. Download **geometry data and test conditions** from the repository links on the Supergen website.
2. Perform blind predictions.
3. Download example data **submission file** and submission data formatting guide from the repository links on the Supergen website.
4. Upload data in specified format to us.



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Data Depository & Test Conditions

- **Turbine geometry:**
  - 3D CAD geometry of nacelle and tower
  - 2D hydrofoil sections / chord and twist distributions
  - 2D hydrofoil CFD data and link to experimental data
  - 3D CAD geometry of blade
- **Turbulence grid geometry:**
  - 3D CAD data
- **Test conditions:**
  - TSR range / flow velocities
  - Measured wave heights and frequencies

Benchmarking Test Cases

- The table below illustrates all the wave conditions tested during the March 2025 campaign, all cases are tested under a tow-speed of $1.0\ m/s$ and a rotation RPM of 72.0 ($TSR \approx 6.03$)
- Depending on the modelling methodology simulation of more or less cases may be possible
- The **blue** cases are the cases with best quality data, and those with the "**Priority**" tag are the ones **requested to be attempted by all simulation methodologies**. Other cases are optional and welcomed.
- 7 solid wave gauges and 6 ultrasonic probes mounted on the carriage to measure wave elevation. U1 signals are used as the reference wave elevation.

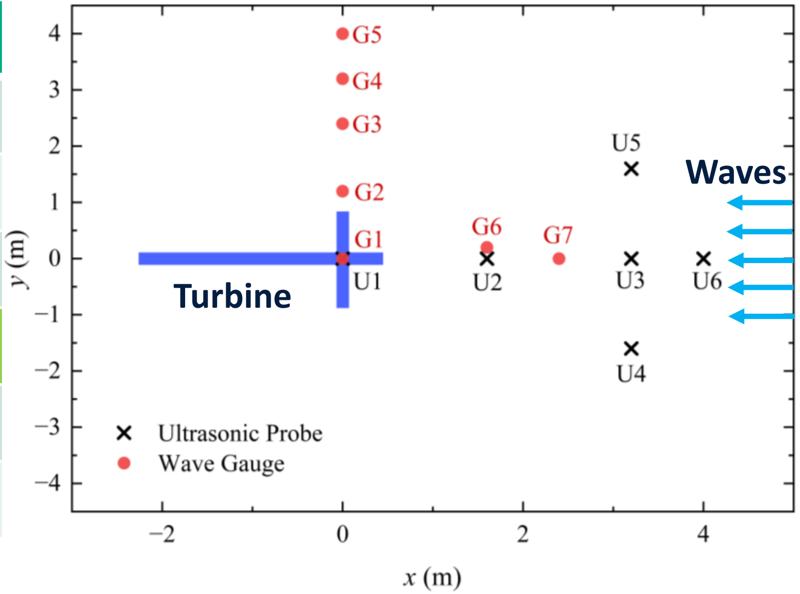
Wave Test Matrix

	Wave Paddle Frequency [Hz]							
Wave Amplitude [m]		0.225	0.25	0.3	0.35	0.4	0.45	0.5
	0.025			Priority				
	0.035							
	0.05	Priority	Priority	Priority		Priority		Priority
	0.075							
	0.1			Priority		Priority		

Blue: Best quality data **Green: More limited data available**

Priority: overlap cases from both 2022 and 2025 campaigns - previously specified for benchmarking

Wave Gauge Locations

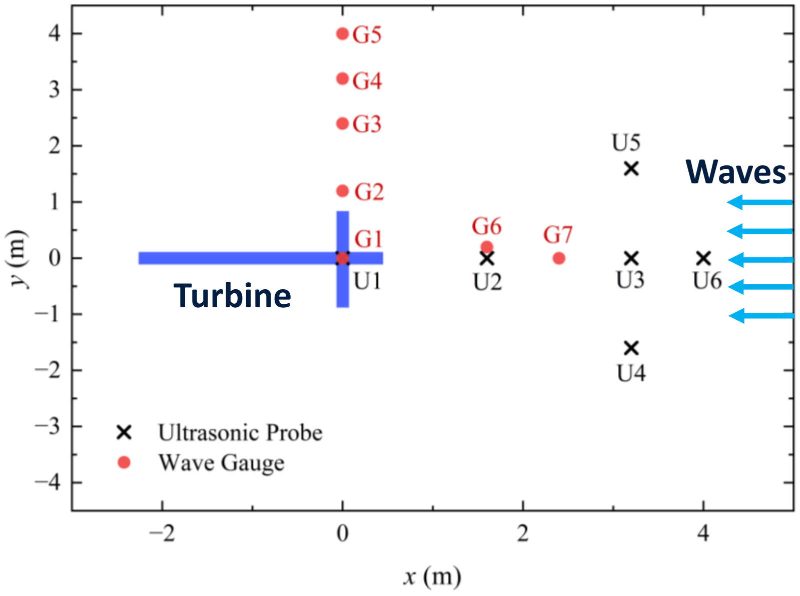


Benchmarking Test Cases

- The previously mentioned wave case frequencies are the **wave paddle frequencies**.
- A table is provided below to translate between the **wave paddle frequency** and the **rotor encounter wave frequency** using the wave dispersion equation.

Wave Paddle Frequency f_0 [Hz]	0.225	0.250	0.300	0.350	0.400	0.450	0.500
Wave Number k	0.238	0.278	0.375	0.498	0.646	0.816	1.007
Wave Celerity c_0 [m/s]	5.945	5.649	5.023	4.415	3.892	3.465	3.119
Wave Encounter Velocity c_0 + Uinf [m/s]	6.945	6.649	6.023	5.415	4.892	4.465	4.119
Wave Encounter Frequency f_en [Hz]	0.263	0.294	0.360	0.429	0.503	0.580	0.660
Wavelength L [m]	26.424	22.595	16.743	12.615	9.730	7.700	6.239
h/L	1.284	1.502	2.027	2.689	3.487	4.406	5.439

Wave Gauge Locations



Data submission format

- Folder structure
  - group_name (zipped folder)
    - method_name01
      - readme (file)
      - meanData (file)
      - phaseData (folder)
        - waveFxxAxx
        - waveFxxAxx
    - method_name02

Please be noted that the numbers in the waveFxxAxx filename needs to be exactly **3 decimal places**.

	Wave Paddle Frequency [Hz]							
Wave Amplitude [m]		0.225	0.250	0.300	0.350	0.400	0.450	0.500
	0.025			waveF0.300A 0.025				
	0.035							
	0.050	waveF0.225A 0.050	waveF0.250A 0.050	waveF0.300A 0.050		waveF0.400A 0.050		waveF0.500A 0.050
	0.075							
	0.100			waveF0.300A 0.100		waveF0.400A 0.100		

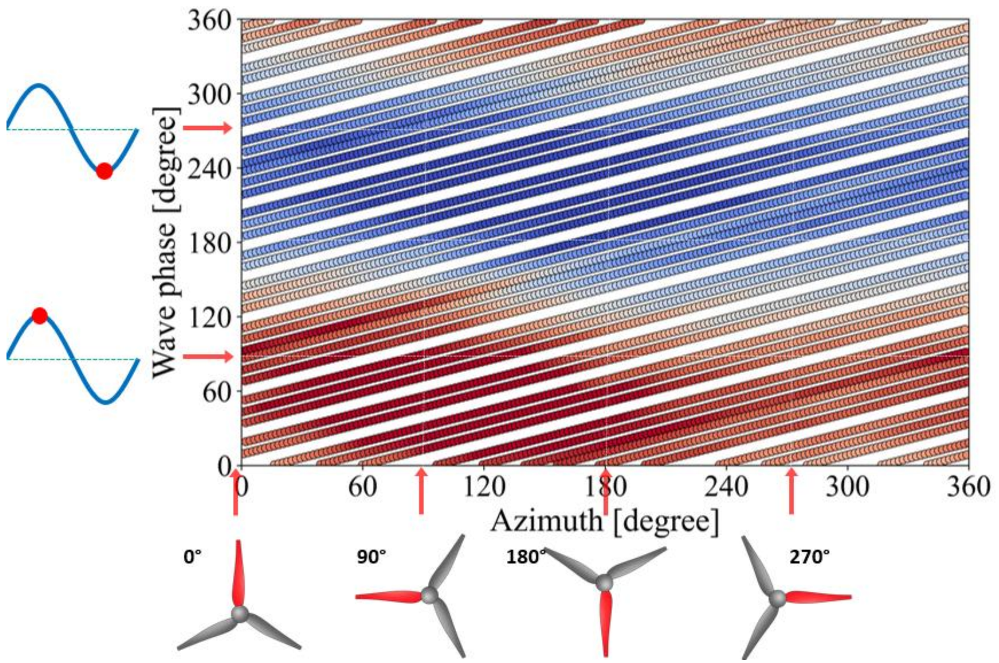
Data submission format

- Format of the **readme** file: include necessary detail of the simulation methodology, sub-models, assumptions, conditions, domain size etc.
- Format of the **meanData** file:
  - Include time-averaged rotor integrated quantities from all simulated wave cases.
  - File format: **tab-delimited ASCII file**, with header line of parameter names start with "#", and each column separated by a tab, numbers should be rounded to **6 decimal places**.
  - Ct: thrust coefficient, Cp: power coefficient, RBM: root bending moment, FW: flapwise, EW: edgewise
  - mean: time-averaged data, SE: standard error $\sigma_{\overline{C_T}} \approx \frac{\sigma_{C_T}}{\sqrt{n}}$, STD: standard deviation

#wave Amplitude [m]	waveFrequency [Hz]	Ct (mean)	Ct (SE)	Ct (STD)	Cp (mean)	Cp (SE)	Cp (STD)	RBM_FW (mean) [Nm]	RBM_FW (SE) [Nm]	RBM_FW (STD) [Nm]	RBM_EW (mean) [Nm]	RBM_EW (SE) [Nm]	RBM_EW (STD) [Nm]
0.025000	0.225000	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
0.025000	0.250000	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
etc.													

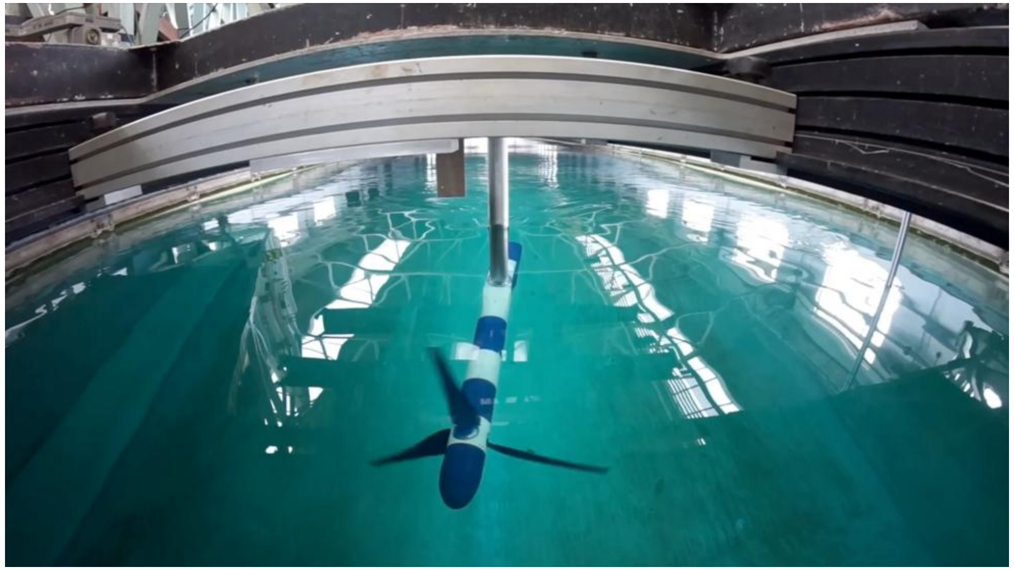
Data submission format

➢ Format of the **phaseData** file
  - Include **time- and phase-history data** (Ct, Cp, RBMs) of a **single blade** for each **extracted/sampled timestep** with calculated **wave and rotational phase angles** (examples on the right).
  - <u>*Note: history of all 3 blades can be included with a shifted rotational phase to increase the data size.*</u>
  - File format: **tab-delimited ASCII file**, with header line of parameter names start with "#", and each column separated by a tab, numbers should be rounded to up to **6 decimal places**.
  - Arranged as below:



#physicalTime [s]	wavePhase [deg]	bladePhase [deg]	Ct	Cp	RBM_FW [Nm]	RBM_EW [Nm]
0.000001	0.00000	xxx	xxx	xxx	xxx	xxx
0.000002	3.00000	xxx	xxx	xxx	xxx	xxx
etc.						

Advice for Modellers



- The exercise is **not a competition** but aims to improve the understanding of the relative strengths and weaknesses and limitations of the different modelling approaches,
- Experiments are also **imperfect** so we do not expect any simulation data to perfectly match the measurements.

Benchmarking Timeline

- Register your participation in the Stage II: Unsteady Loading in Waves benchmarking exercise by email to Xiaosheng Chen xiaosheng.chen@eng.ox.ac.uk
- 31st October 2025 Webinar with registered participants to clarify case set up and data submission requirements.
- Nov / Dec 2025 (TBC) optional progress Webinar
- Submit your blind prediction loading solutions by 16th January 2026.

Participation & benchmarking data

For further details on the Tidal Turbine Benchmarking Project, including benchmark data and how to take part:

https://supergen-ore.net/projects/tidal-turbine-benchmarking

Email Richard Willden Richard.Willden@eng.ox.ac.uk

or Xiaosheng Chen xiaosheng.chen@eng.ox.ac.uk

Stage I – Uniform Flow benchmarking data

Data repository currently being uploaded to the website (in the "Released Data Log")
Experimental data: Tucker Harvey et al. "Tidal Turbine Benchmarking Project: Stage I – Steady Flow Experiments"
Blind predictions: Willden et al. "Tidal Turbine Benchmarking Project: Stage I – Steady Flow Blind Predictions"
Full comparisons in companion Journal Articles in submission to *Journal of Fluids & Structures*

Stage II – Unsteady Loading benchmarking data

Data to be made available following final submissions to the blind prediction exercise on 16th January 2026
Wave loading data analysis … in preparation
Yawed loading data analysis … in preparation

Supergen Offshore Renewable Energy | University of Oxford | University of Bath | The University of Edinburgh | University of Hull | Manchester 1824 The University of Manchester | UKRI Engineering and Physical Sciences Research Council