Tidal Benchmarking Project:
Opening Workshop

Oxford: Richard Willden, Sam Tucker Harvey, Xiaosheng Chen, Chris Vogel
Hull: Jim Gilbert, Kaushal Bhavsar, Tom Allsop
Manchester: Tim Stallard, Hannah Mullings
Bath: Anna Young, Ian Benson

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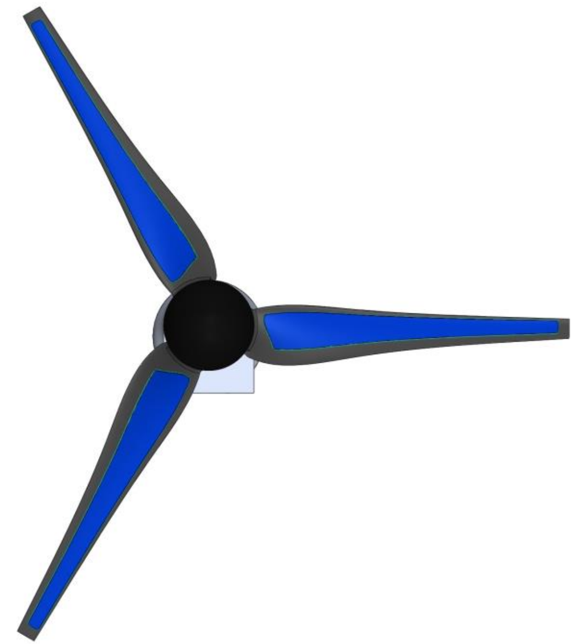
Supergen Offshore Renewable Energy | University of Oxford | University of Hull | Manchester 1824 The University of Manchester | University of Bath | UKRI Engineering and Physical Sciences Research Council

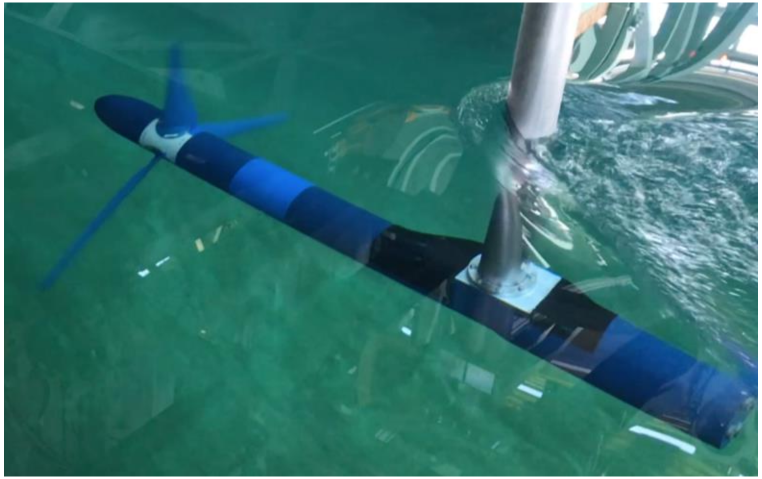
Agenda

1. Introduction and overview of tidal benchmarking project
2. Turbine hydrodynamic design
3. Turbine mechanical design and instrumentation
4. Description of experiments and test conditions
5. Overview of geometry data, benchmarking cases and advice for modellers
6. How to participate
7. Questions and open discussion



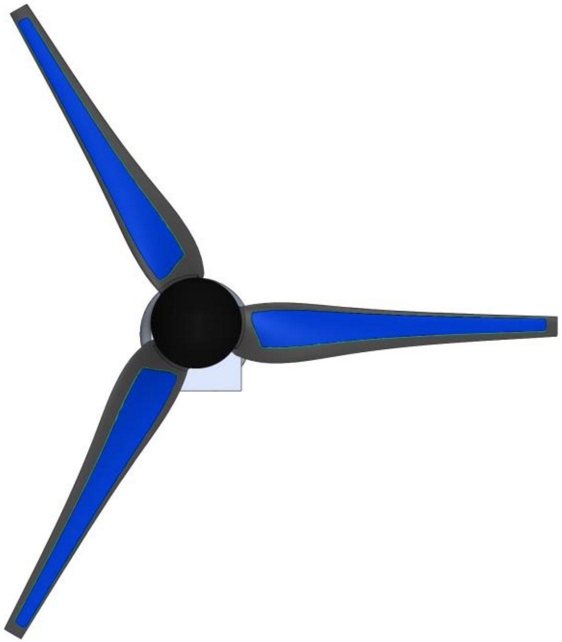
Benchmarking Project: Overview and Objectives

- ***Unsteady loading and the inability to confidently predict unsteady loading and / or quantify errors drives unnecessary redundancy and design conservatism.***
- **Objectives**:
  - i. improve accuracy of modelling techniques,
  - ii. improve confidence in the use of modelling techniques,
  - iii. quantify modelling errors for different techniques under different loading scenarios,
  - iv. development of novel measurement techniques.
- **Approach**:
  - i. Conduct a large laboratory test of a highly instrumented tidal turbine in waves and turbulent current to provide underlying data,
  - ii. Conduct a series of community wide (academia and industry) blind prediction exercises with staged data release, leading to an open access dataset



Benchmarking Project: Turbine requirement

- Validation data sets (MEXICO, NREL IV etc) exist for wind.
- Whole rotor and whole blade data sets (Bahaj, Ifremer etc) exist for tidal, i.e. rotor torque/thrust and blade root bending.
- To understand and be able to predict the impact of waves and turbulence on blade loads we need a higher data resolution in the form of **spanwise loading distributions**.
- Require **in-blade sensing** (strain gauges, fibre Bragg).
- Critically important to achieve **Reynolds number independence**.
- **1.6m diameter 3 bladed rotor** with in-blade sensing.



Requirements, Tests & Facility

Test requirements:

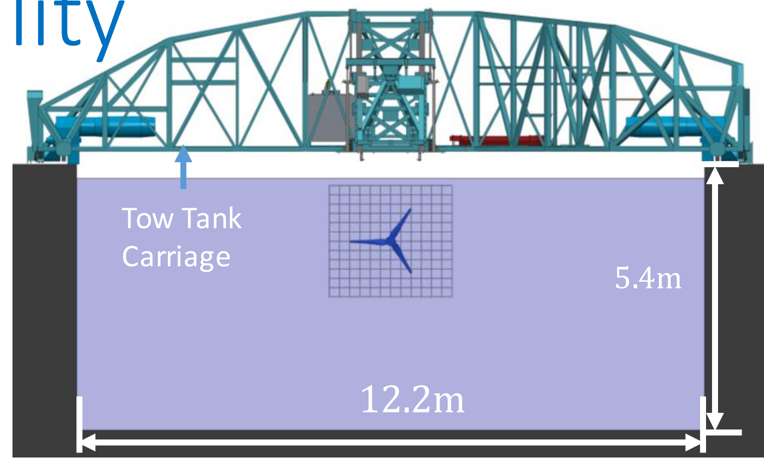
- Require **low blockage** experiments with a **large diameter** rotor for **in-blade sensing** and **Reynolds independence**.
- Flume options – blockage too high
- Tow tank – low blockage but turbulence low.
- Solution: **tow tank with an upstream turbulence grid**

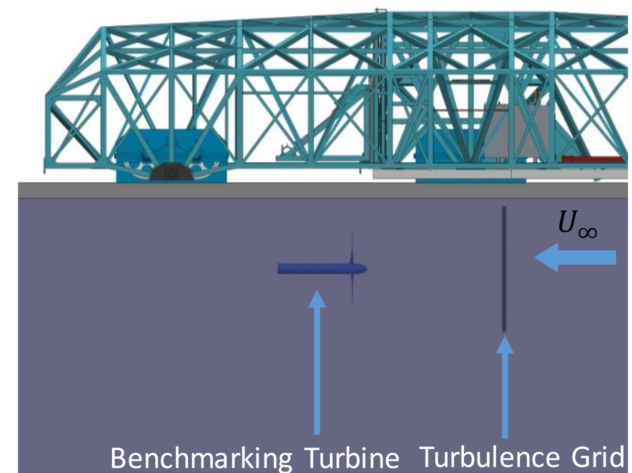
Test conditions:

- Uniform flow
- Uniform flow + Waves
- Uniform flow + Grid generated turbulence

QinetiQ towing tank facility, Haslar, Portsmouth UK

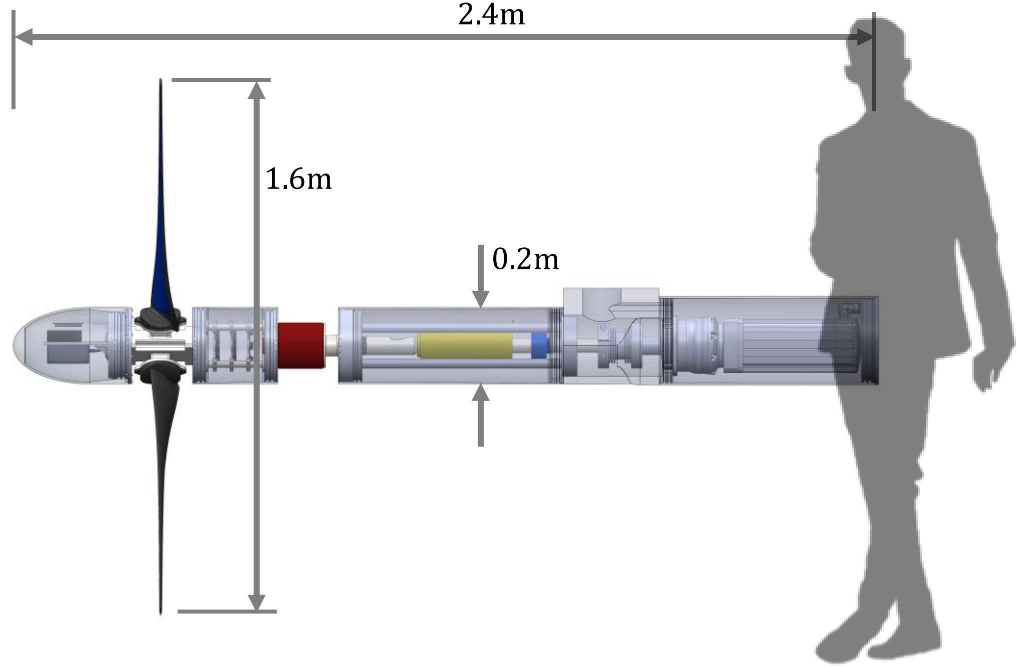
- 270m (L) x 12.2m (W) x 5.4m (D)
- Tow speed 1m/s
- Tow length approx. 150m
- Settling time ~15mins





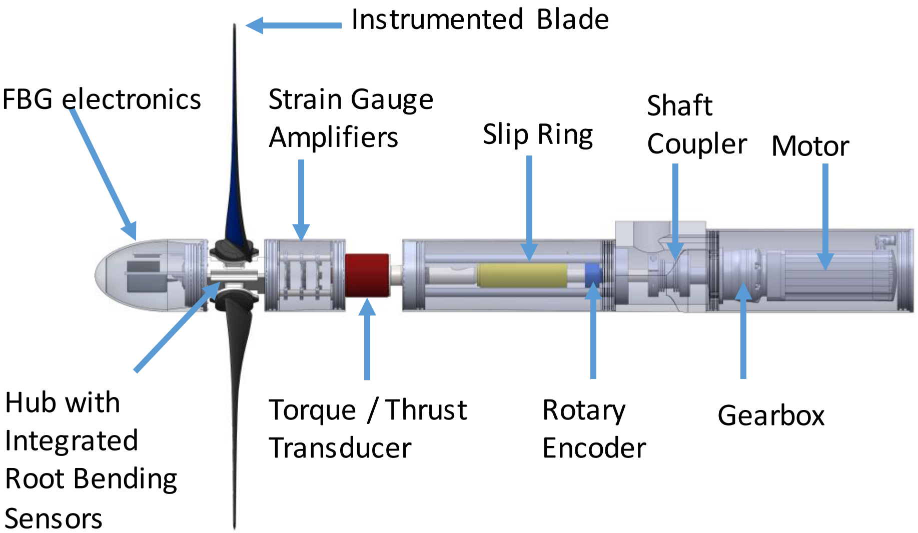
Turbine Design: Overview

- 3 bladed tidal rotor
- Top mounted (carriage-mounted for towing tank experiment)
- $0.2\mathrm{m}$ nacelle diameter provides d_n/D of 0.125.
- Nacelle diameter increased to $0.248\mathrm{m}$ to accommodate large Moog servo motor

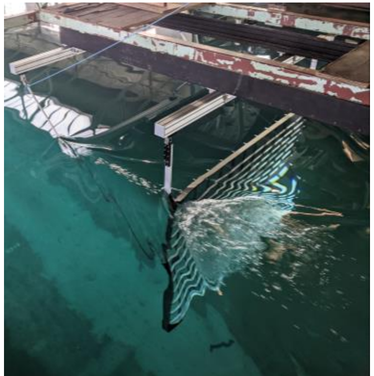


Turbine Design: Overview

- Two blades instrumented with strain gauges at six radial locations in both edgewise and flapwise directions.
- Remaining blade instrumented with fibre Bragg sensors with similar resolution.
- Individual blade loads measured with hub – integrated root bending sensors (flap and edge).
- Torque and Thrust measured by shaft mounted transducer upstream of front bearing.
- Shaft rotary encoder for speed and position on low speed side.
- Motor and encoder on high speed side.



Timeline

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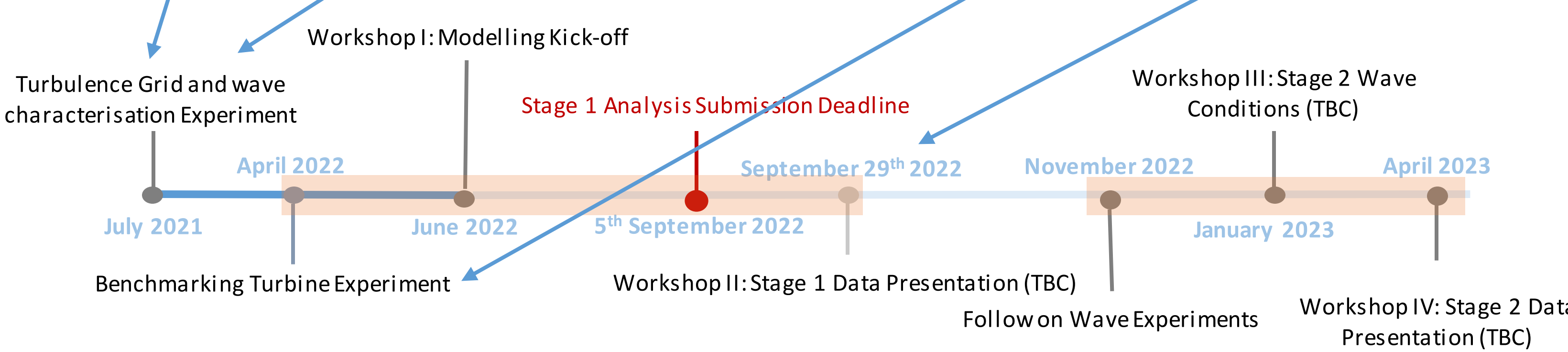
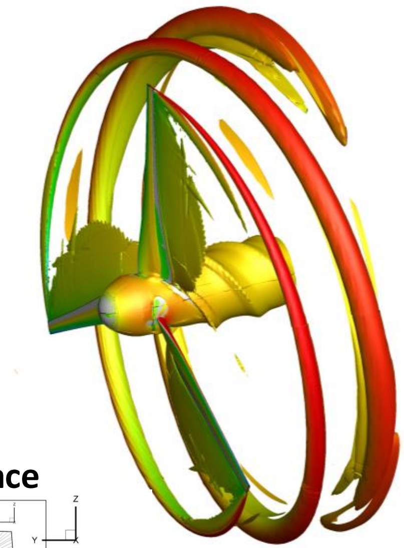
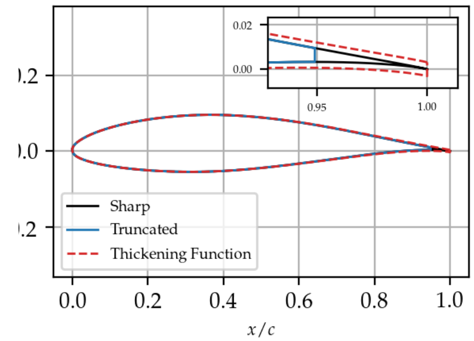

Workshop I: Modelling Kick-off
Turbulence Grid and wave characterisation Experiment
Stage 1 Analysis Submission Deadline
Workshop III: Stage 2 Wave Conditions (TBC)
April 2022
September 29th 2022
November 2022
April 2023
July 2021
June 2022
5th September 2022
January 2023
Benchmarking Turbine Experiment
Workshop II: Stage 1 Data Presentation (TBC)
Follow on Wave Experiments
Workshop IV: Stage 2 Data Presentation (TBC)

Rotor Design Process

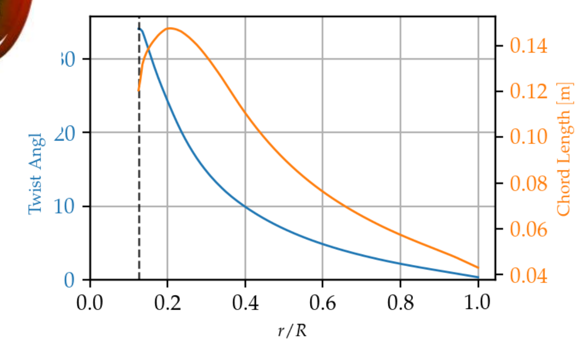
- Rotor designed for facility and operating conditions
- Considerations: $U = 1\ m/s, Tu = 5\%$
- Post-critical blade **Re >200k**
- Uniform hydrodynamic profile along span to simplify modelling
- Low blockage (3.05%)
- Design method**: RANS embedded BE solver**



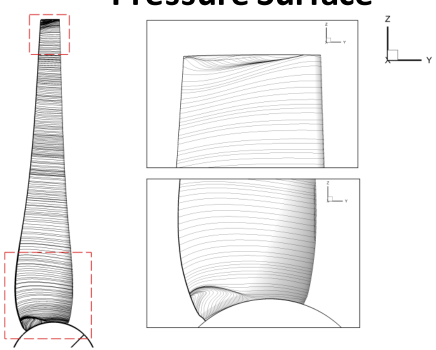


Blade profile

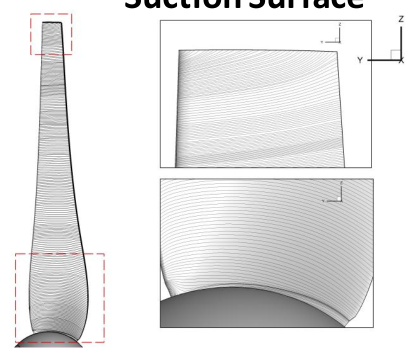
Chord & Twist



Pressure Surface

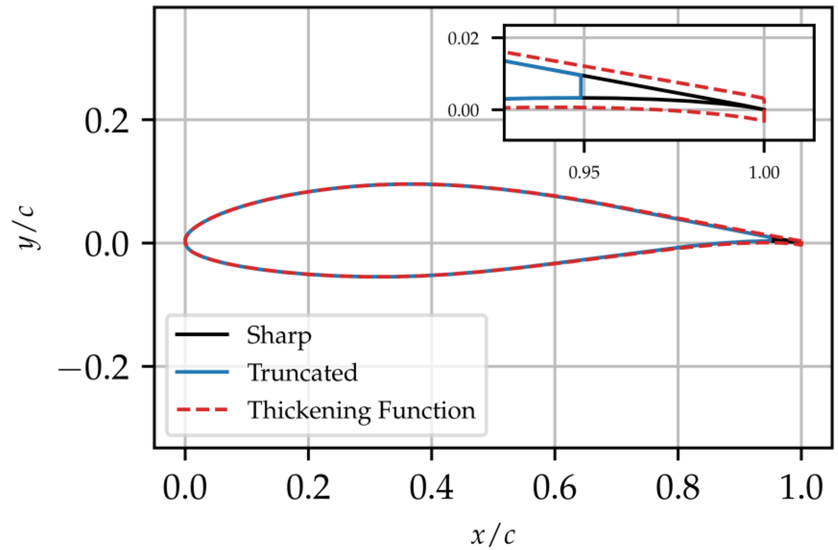


Suction Surface



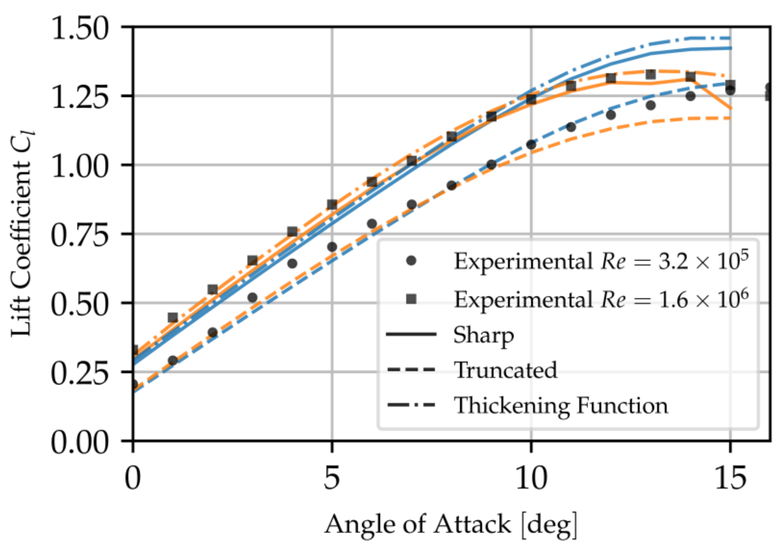
2D Hydrofoil Validation

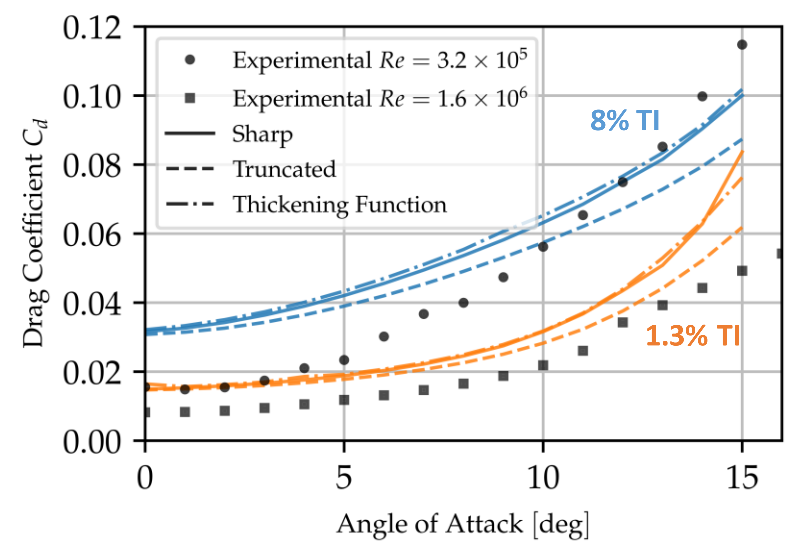
- The chosen hydrofoil profile is **NACA 63-415**, this profile and the variations of it (63-815, 63-415- Risø-D) has been used both by researchers (X-med, Risø) and industry company (Alstom).
- **Single hydrofoil profile** utilised for blade design to simplify modelling process
- Non-dimensional trailing edge thickness maintained constant along span $t_e/c = 0.625\%$
- The hydrodynamics of the hydrofoil is examined, especially on the trailing edge treatment:
    a) Sharp trailing edge
    b) Thickened trailing edge
    c) Truncated trailing edge



2D Hydrofoil Validation

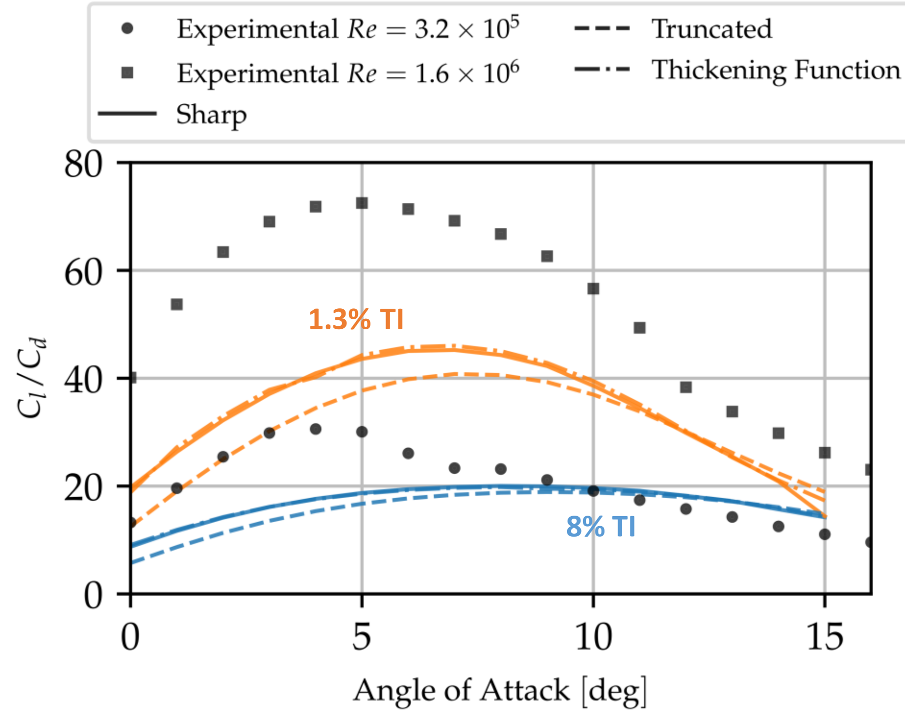
- Target Reynolds number of **300,000**
- Lift and drag coefficients obtained from the **2D RANS simulations** to compare the truncation methods
- $k - \omega$ SST turbulence model with $y^+ \sim 1$





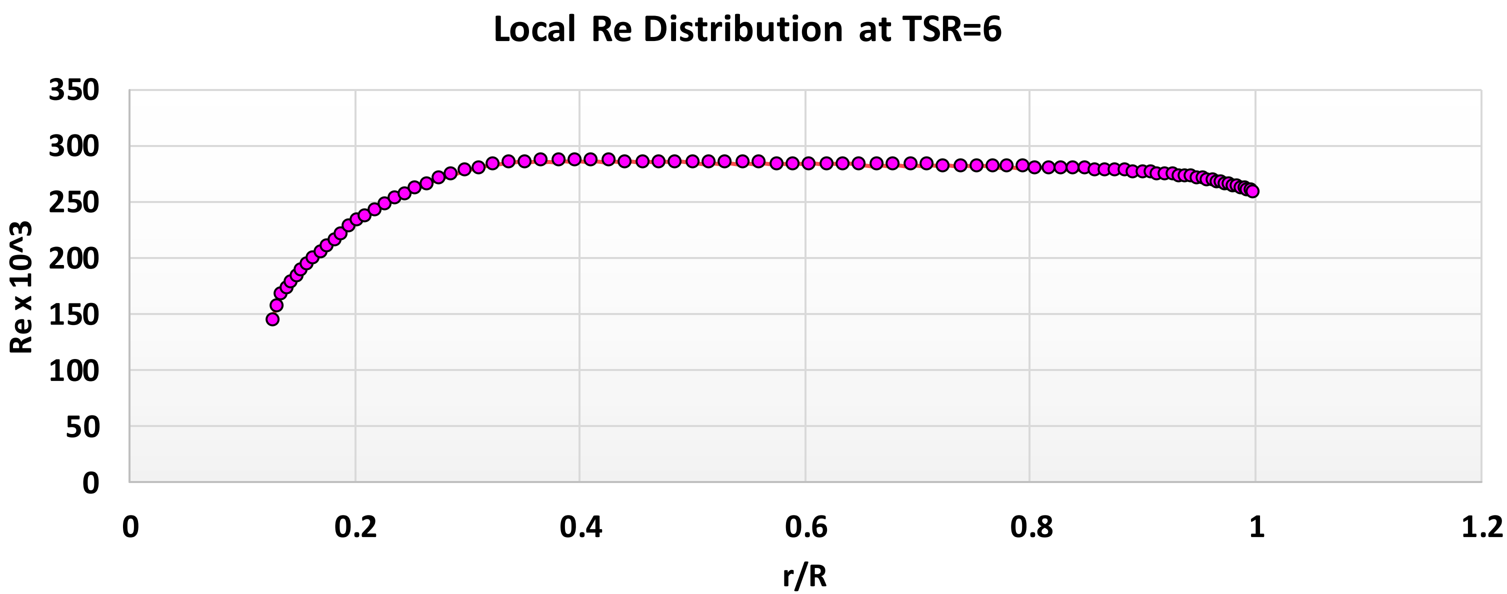
2D Hydrofoil Validation

- Truncated hydrofoil has reduced lift to drag performance
- Thickened hydrofoil preserves sharp hydrofoil performance
- TI, which varies radial for a turbine, has a significant impact on blade performance



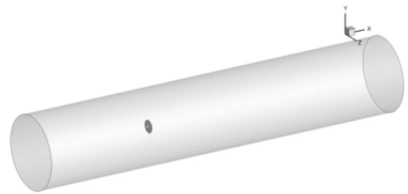
Spanwise Reynolds Number Variation

- Reynolds number distribution generated post blade design simulations
- Reynolds number is approx. to constant between r/R = 0.3 to 0.9

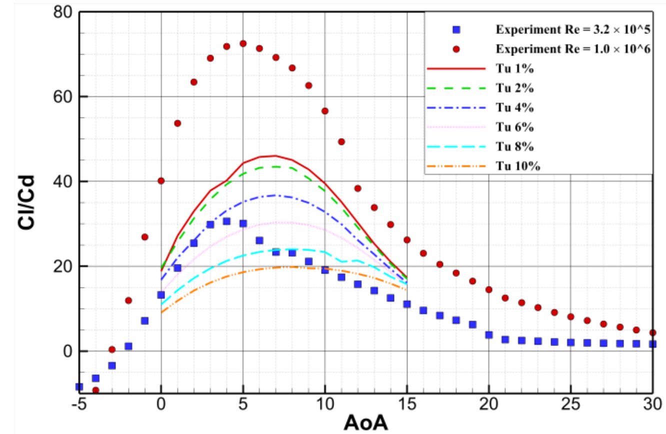


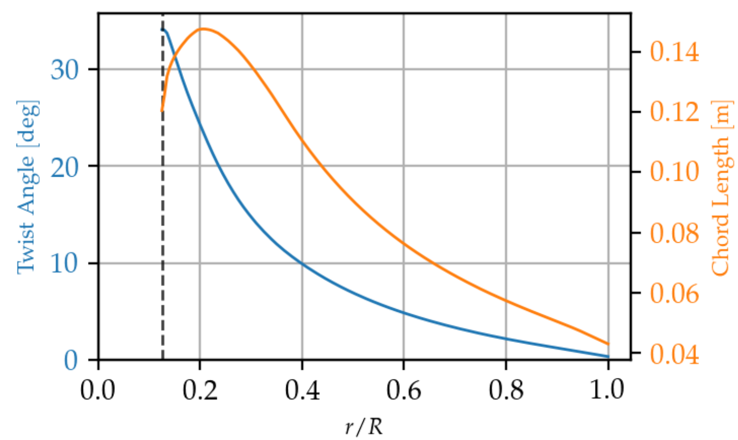
RANS-BE Blade Design

- **Geometry of the simulation:**
  - Rotor diameter = 1.6m
  - nacelle diameter = 0.2m
  - Blockage ratio B = 3.05%

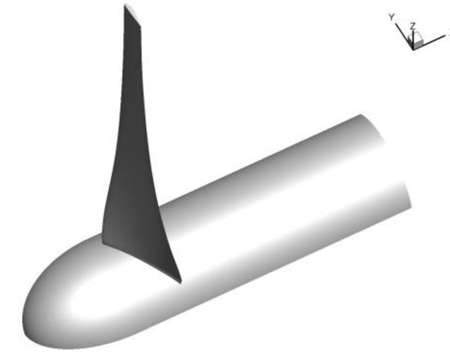


- **Turbine setup:**
  - Blade lift and drag data interpolated along span by Tu
  - Optimal Cl/Cd yields target **AoA = 6deg**
  - Design **TSR = 6.0** (to maintain high Re)
  - CoP = 33% chord
- **Freestream flow conditions:**
  - Inflow speed 1m/s
  - Tu = 5%
- **Design Output:**
  - Twist and chord distributions
  - **34 degree** geometric twist variation
  - Average chord = **87.94mm**
  - Rotor solidity = **0.1746**



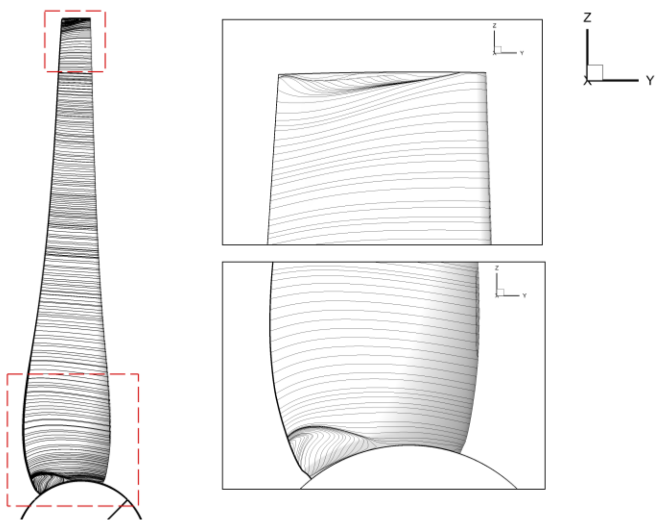


Blade Resolved Rotor Simulation

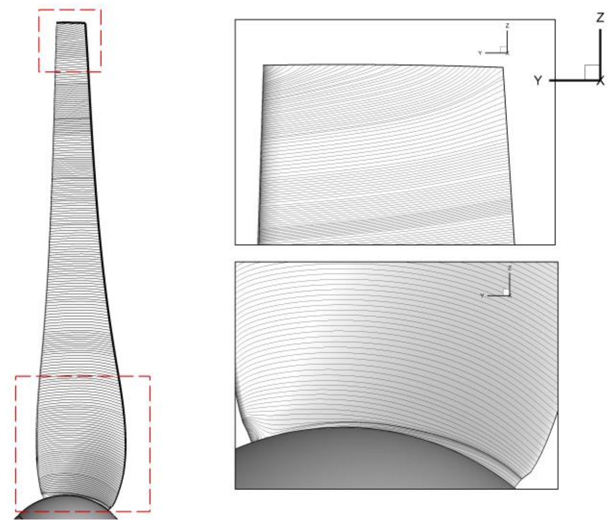


- 3D rendered CAD geometry within Multiple Reference Frame
- Surface streamlines at TSR = 6, inflow Tu=5%
- Highlights root and tip features and departure from BEM assumptions

Pressure Surface

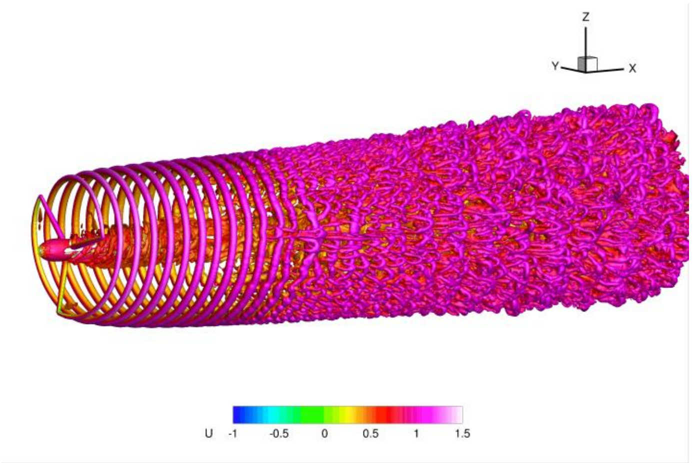


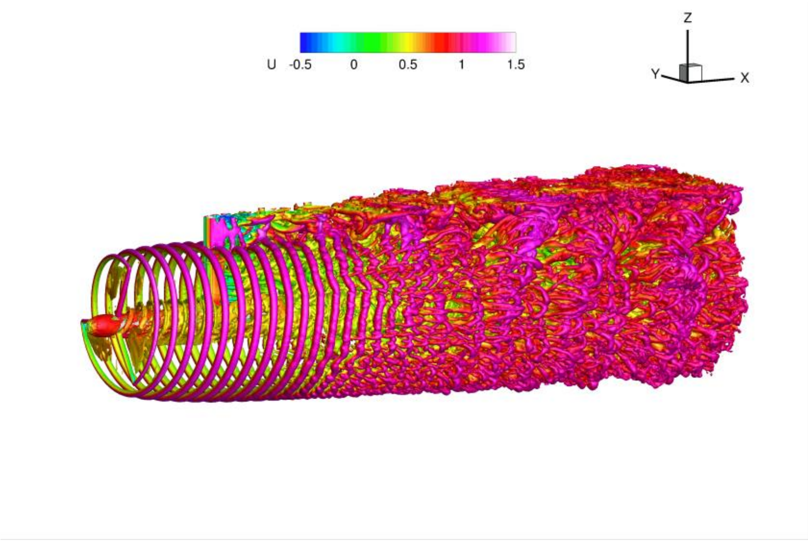
Suction Surface



Visualisation of the Experiment

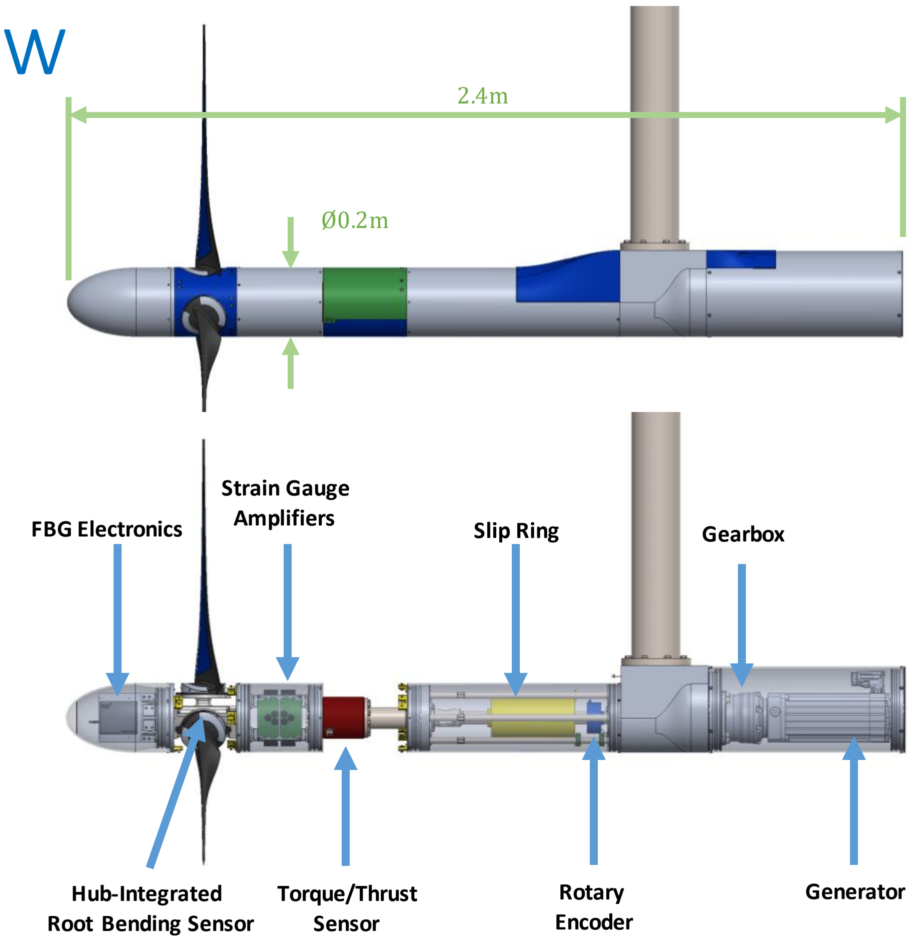
- LES - Actuator Line with 45M cell mesh
- Full Nacelle and tower geometry modelled using an immersed boundary method





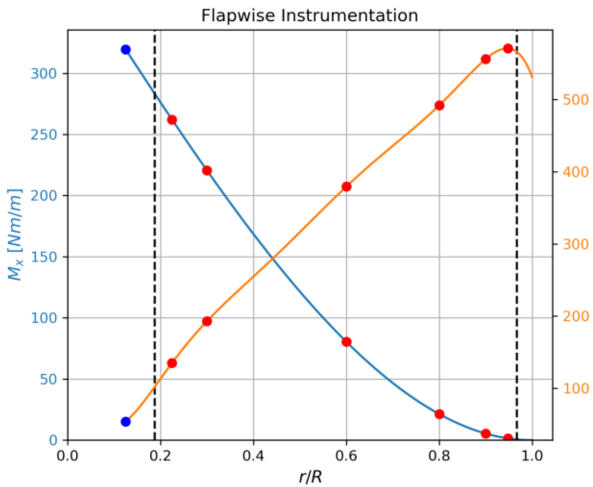
Turbine Design: Overview

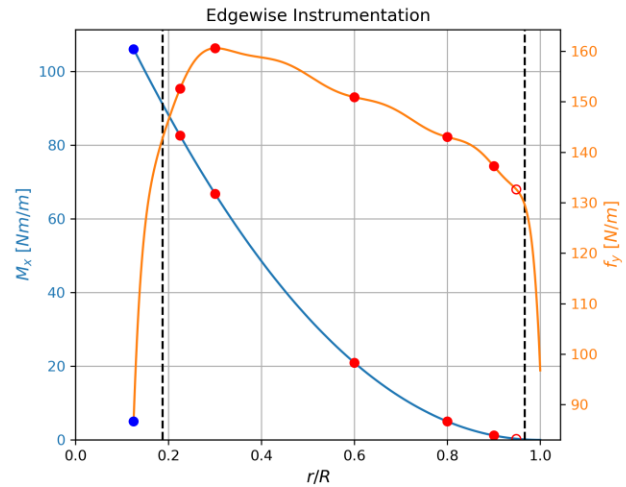
- 1.6m diameter rotor / 0.2m diameter nacelle
- Two blades instrumented with strain gauges at six radial locations for flapwise and edgewise bending moments
- Remaining blade instrumented with fibre Bragg sensors
- Individual root blade moments measured with hub – integrated root bending sensors
- Over 100 individual strain gauges
- Torque and Thrust measured by shaft mounted transducer upstream of front bearing
- Rotary encoder for angular velocity and blade position
- Motor torque and speed

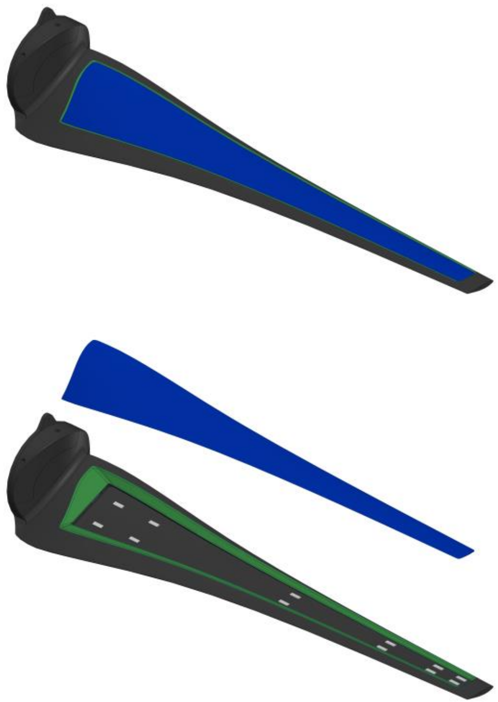


Turbine Design: Instrumented Blades

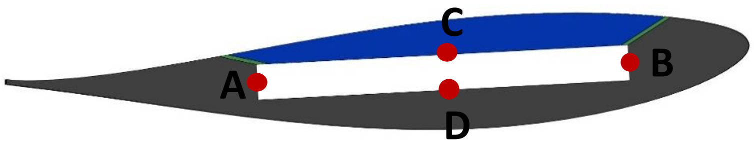
- Two part construction of blade to provide instrumentation channel
- Instrumentation channel twists and tapers with blade with faces aligned with local neutral axes
- Two blades instrumented with strain gauges at six radial locations
- Flapwise bending moment at locations 1-6, edgewise bending moments at locations 1-5



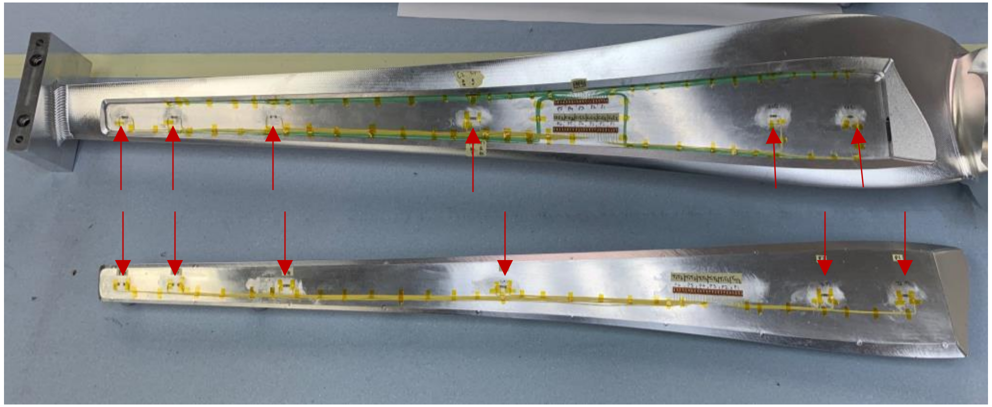




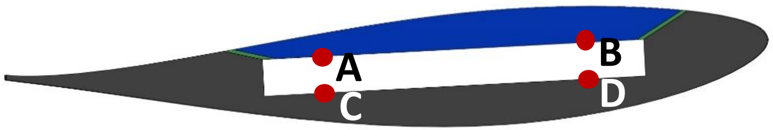
Turbine Design: Instrumented Blades (Strain Gauging)



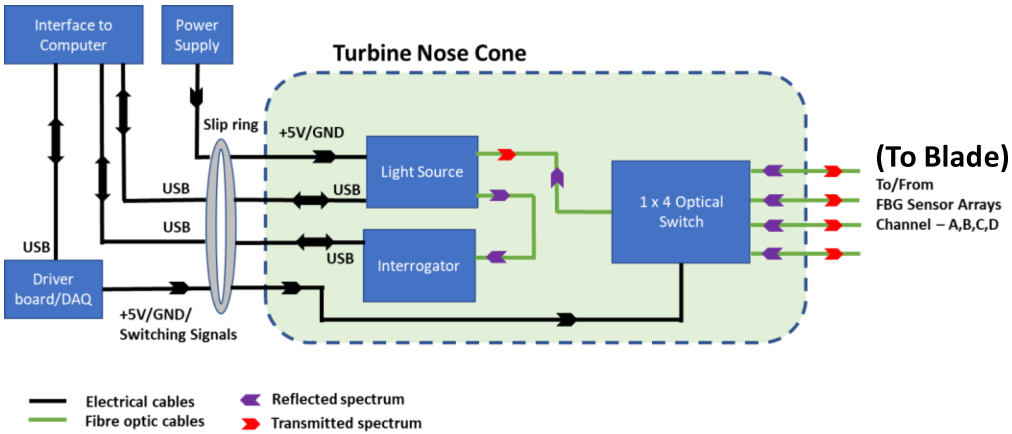
- Positions chosen to minimise cross – talk between measurement directions
- Full bridge configurations for both edgewise and flapwise measurements

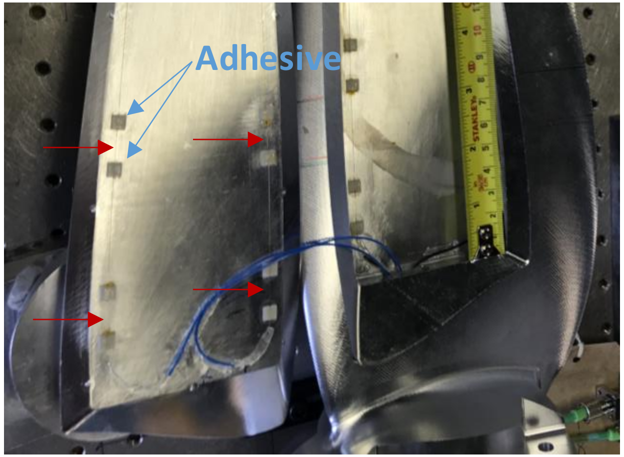


Turbine Design: Instrumented Blades (Fibre Bragg)



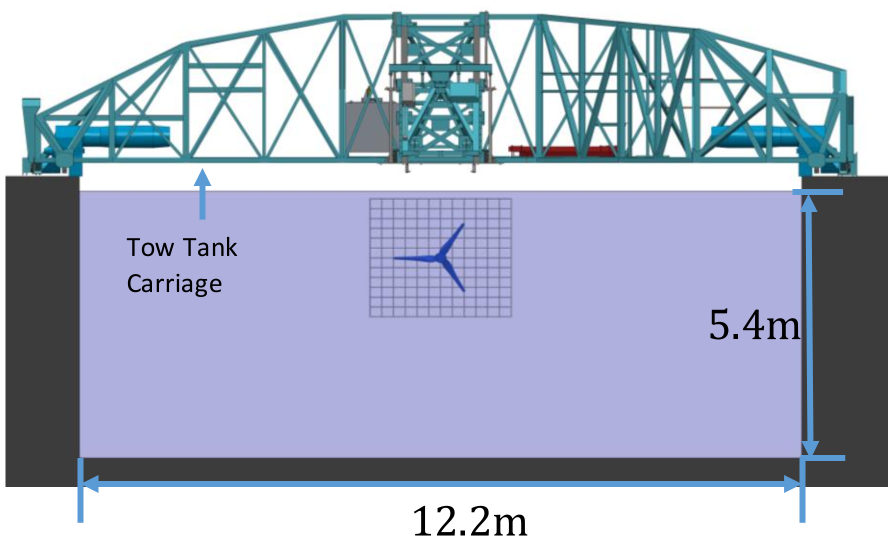
- Sensors located only on pressure and suction sides of internal slot due to size constraints
- To minimise the influence of shear strain the fibre either side of the FBG sensor is adhered with a 12.5mm gap around the sensor

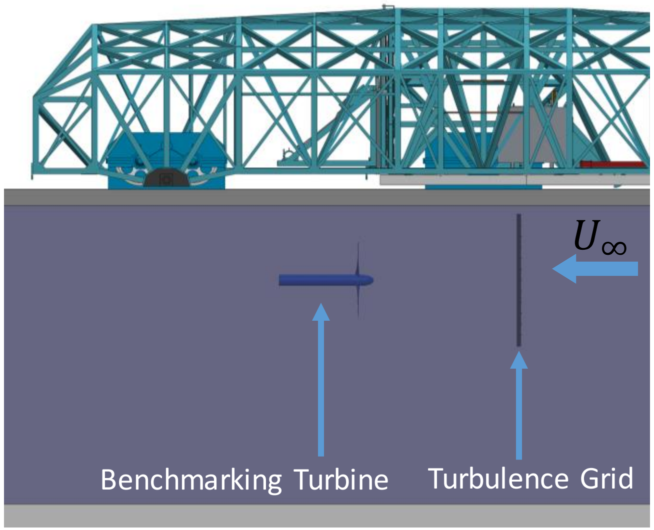




Selected Towing Tank Facility

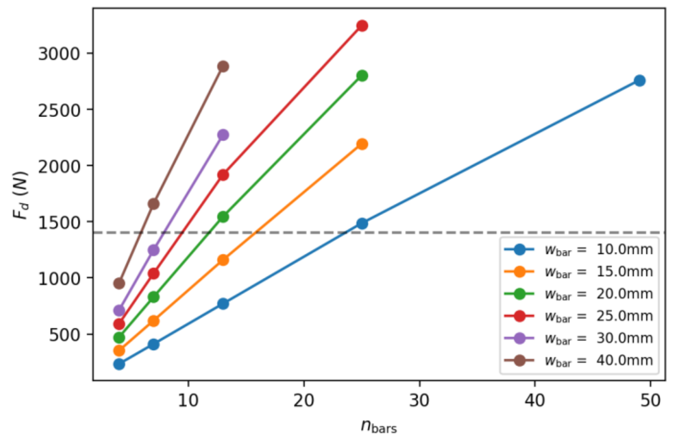
- QinetiQ towing tank facility, Haslar, Portsmouth UK
- 270m (L) x 12.2m (W) x 5.4m (D)
- Speeds of up to **12.25m/s** and drag loads up to **5kN**
- Total load and hence flow speed is restricted due to the drag of the turbulence grid
- Side wall batter of **1/12 slope** (not vertical as shown in figures)

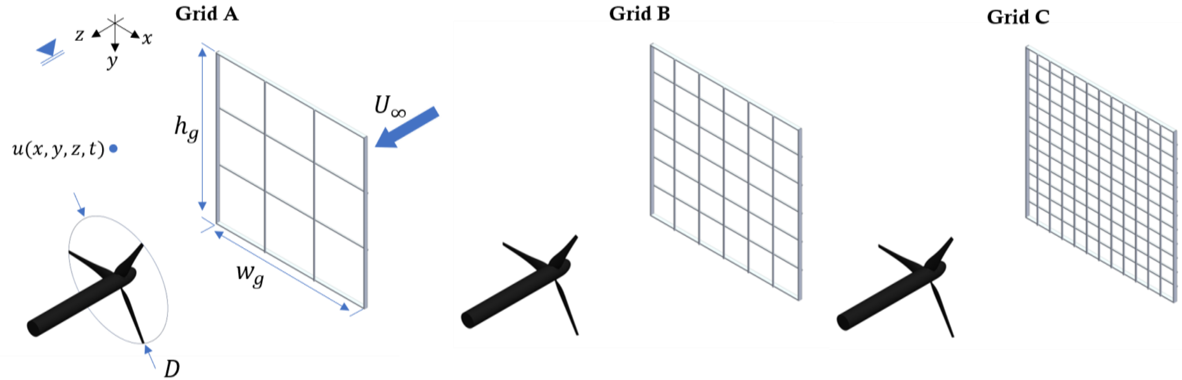


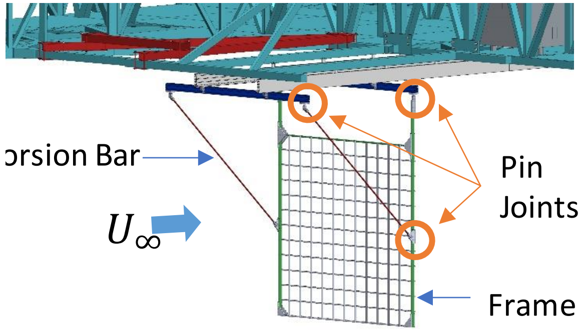


Turbulence Grid: Design

- Size: $1.5D \times 1.5D = 2.4 \times 2.4\text{m}$
- Variable porosity (adjust number of bars)
- Torsion bars used to resist drag force
- Use of pin joints allows the turbulence grid to rotate between a horizontal and vertical configuration

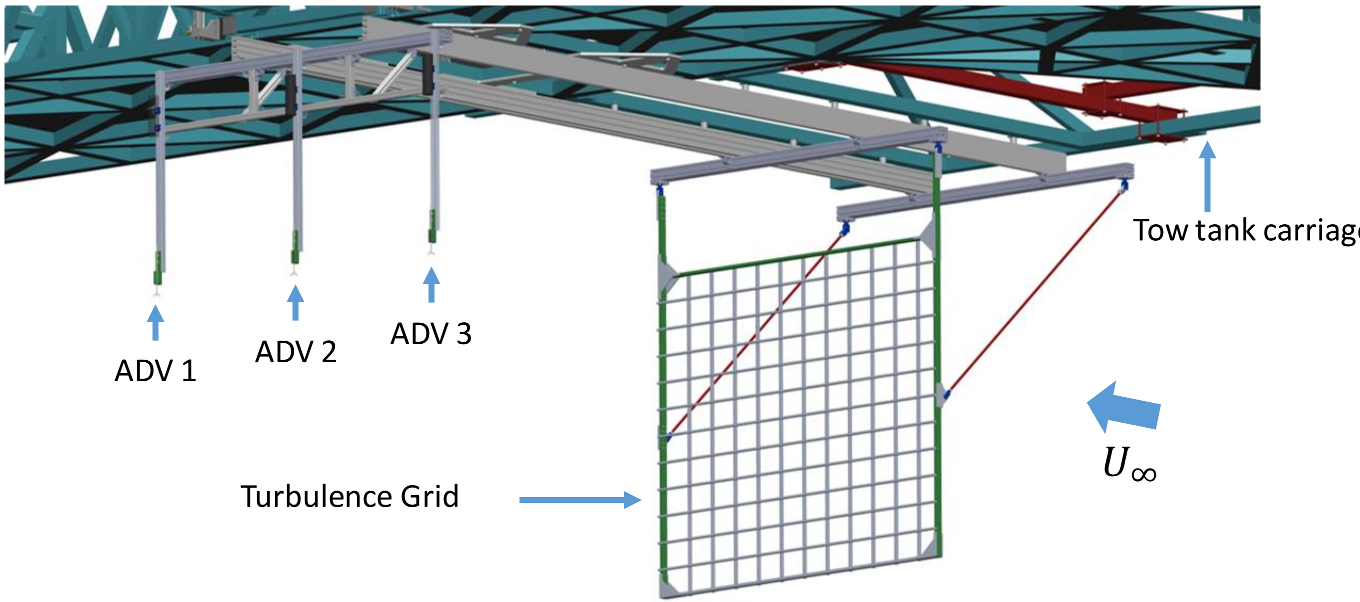






Turbulence Grid: Flow Characterisation (ADV)

- Flow velocity measured with 3 Acoustic Doppler Velocimeter (ADV) probes
- ADV positions varied to obtain a horizontal, vertical and diagonal profiles

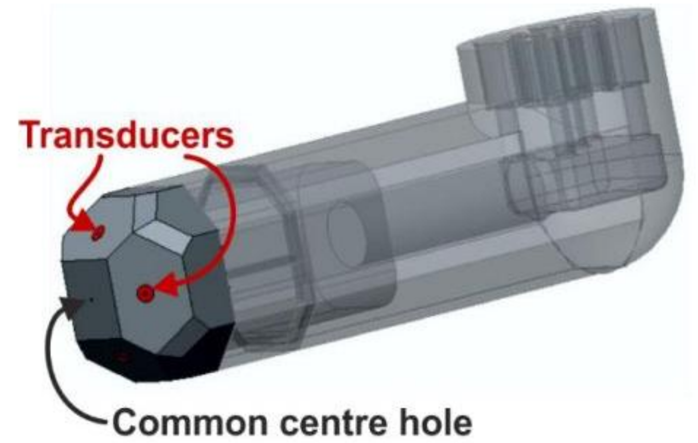


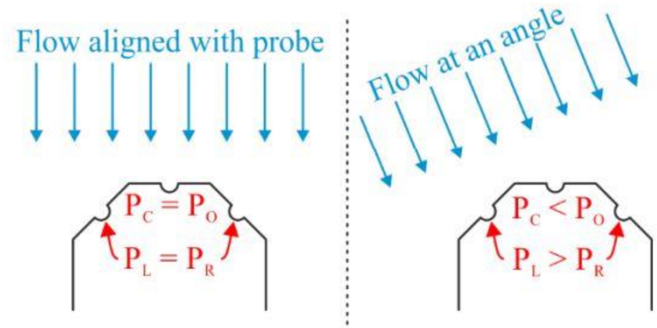
Turbulence Grid: Flow Characterisation (ADV)

- Acoustic Doppler Velocimeters require seeding particles to calculate flow velocities
- The large volume of towing tanks prohibits uniform seeding of the entire tank (17.8 million Litres - £130,000 in seeding material)
- Targeted seeding injected with a pump at the measurement location along the tank prior to test run
- 10 tonnes of seeded water pumped into tank during campaign

Turbulence Grid: Flow Characterisation (Barnacle)

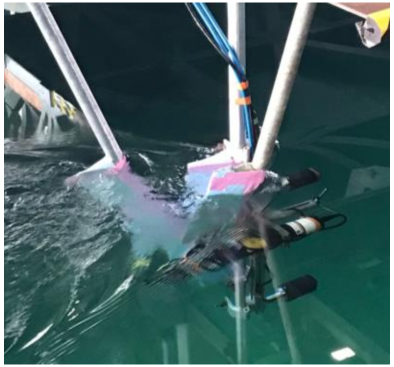
- The Barnacle is an unsteady 5-hole probe developed by Anna Young and Ian Benson, University of Bath
- By combining pressure measurements at the centres of the five faces, the **yaw, pitch and velocity magnitude** can be calculated
- Before the installation of the benchmarking turbine in during the March 2022 campaign flow measurements were made in the wake of the turbulence grid
- The measurements provide a useful verification of the previous ADV measurements as the device operates via a different physical mechanism

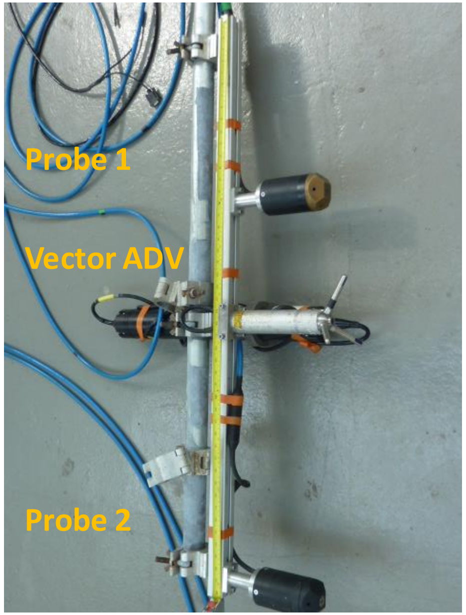




Turbulence Grid: Flow Characterisation (Barnacle)

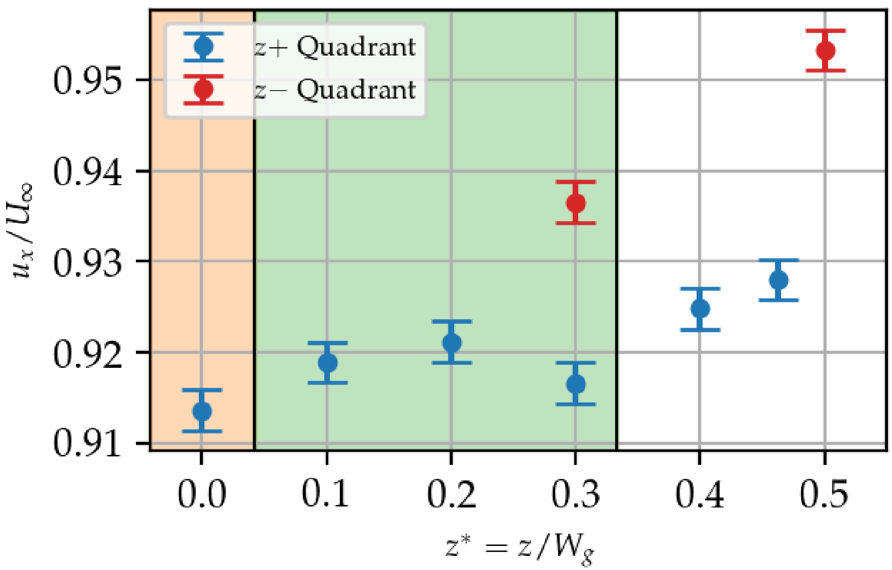
- Two barnacle probes were mounted at different depths with the lowest positioned at the hub depth
- A Nortek Vector ADV was also mounted, although it was unable to provide measurements due to the lack of seeding material
- The integrated IMU on the Nortek Vector did however provide a method of evaluating the carriage vibration





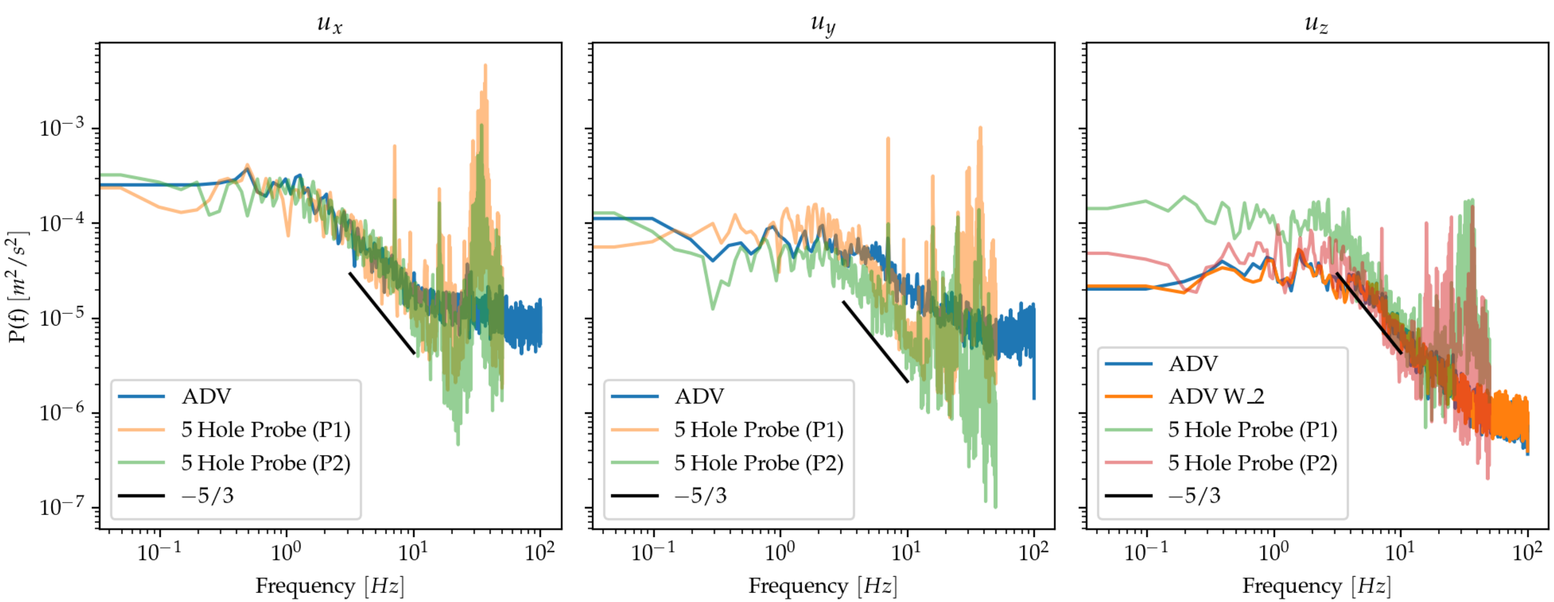
Turbulence Grid: Velocity Profile

- Minimum streamwise velocity of $0.913\ U_\infty$ at centre of turbulence grid
- Area weighted mean of $0.9207\ U_\infty$ across turbine with $\pm 0.5\%$ variation



Turbulence Grid: Turbulence Spectra

- Spectra evaluated with Welch power spectral density estimate
- High frequency peaks in 5 hole probe data relate to carriage vibration
- Correspondence between spectra is relatively close



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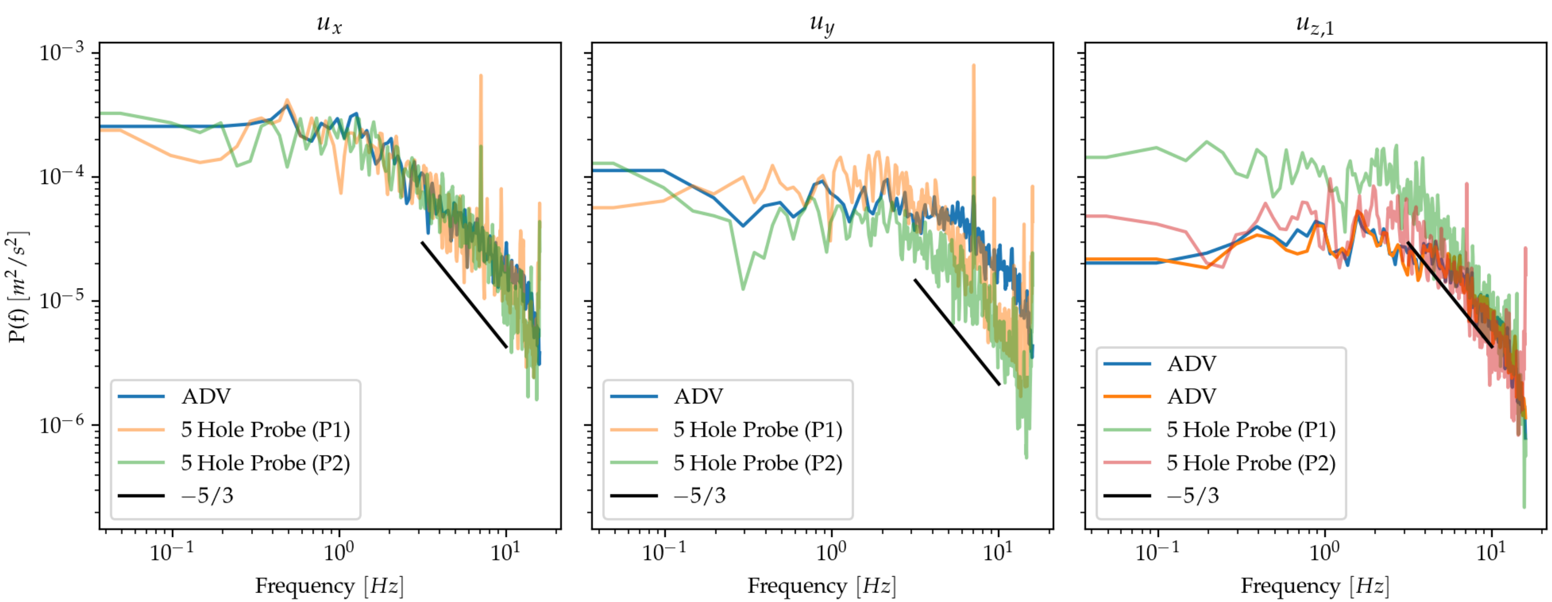
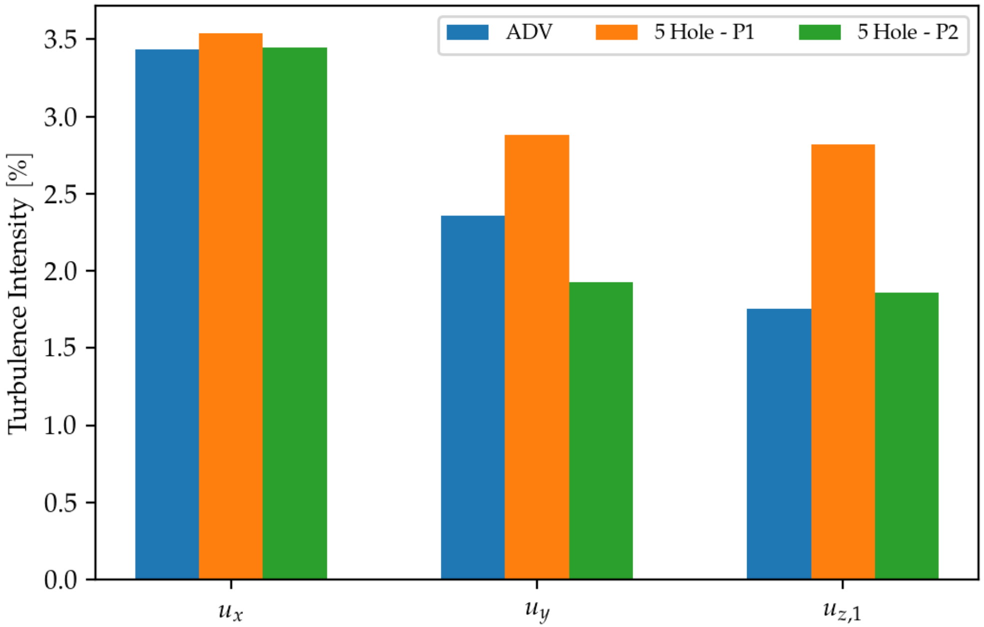


Turbulence Grid: Turbulence Intensities

- Turbulence intensity can be defined as,

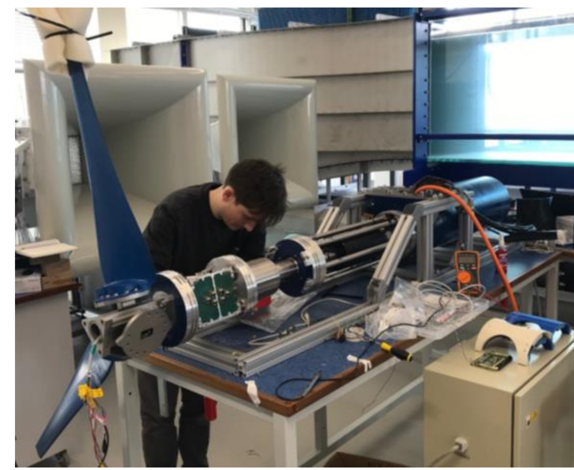
$$I_i = \frac{u'_{i\ \mathrm{rms}}}{\sqrt{\bar{u}_x^2 + \bar{u}_y^2 + \bar{u}_z^2}}$$

- Streamwise turbulence intensity across turbine between 2.8% and 3.5% with an area weighted mean of 3.1%
- Lower turbulence intensity than typical in the field but a well defined condition for testing simulations and engineering models



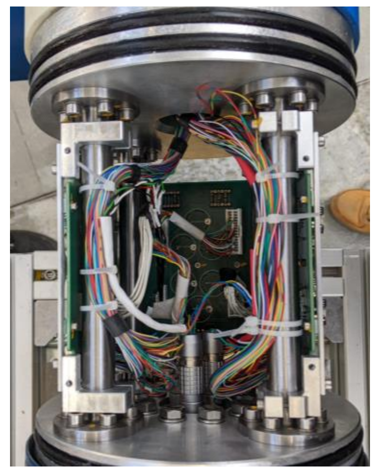
April 2022 Experimental Campaign

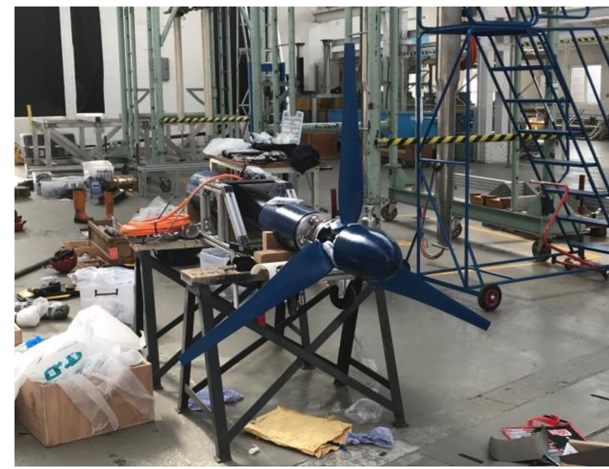
- Data was successfully obtained for all steady and turbulent flow conditions during the **April 2022 campaign**
- A selection of wave cases were also completed, with further wave testing scheduled for **November 2022**



April 2022 Experimental Campaign

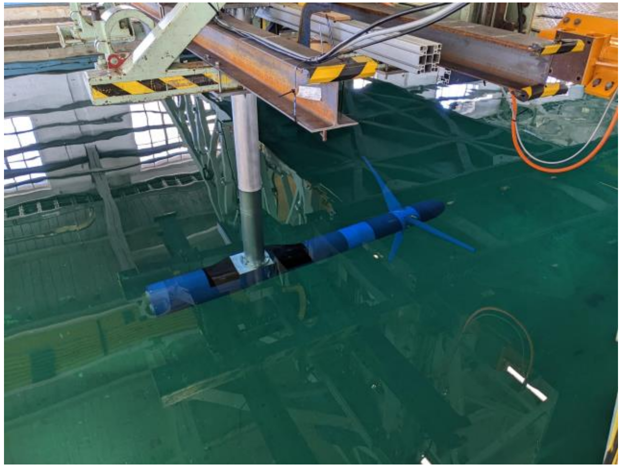
- Corrosion resistant coating to protect blades and nacelle from anodic damage
- Sacrificial anodes mounted to rear of nacelle





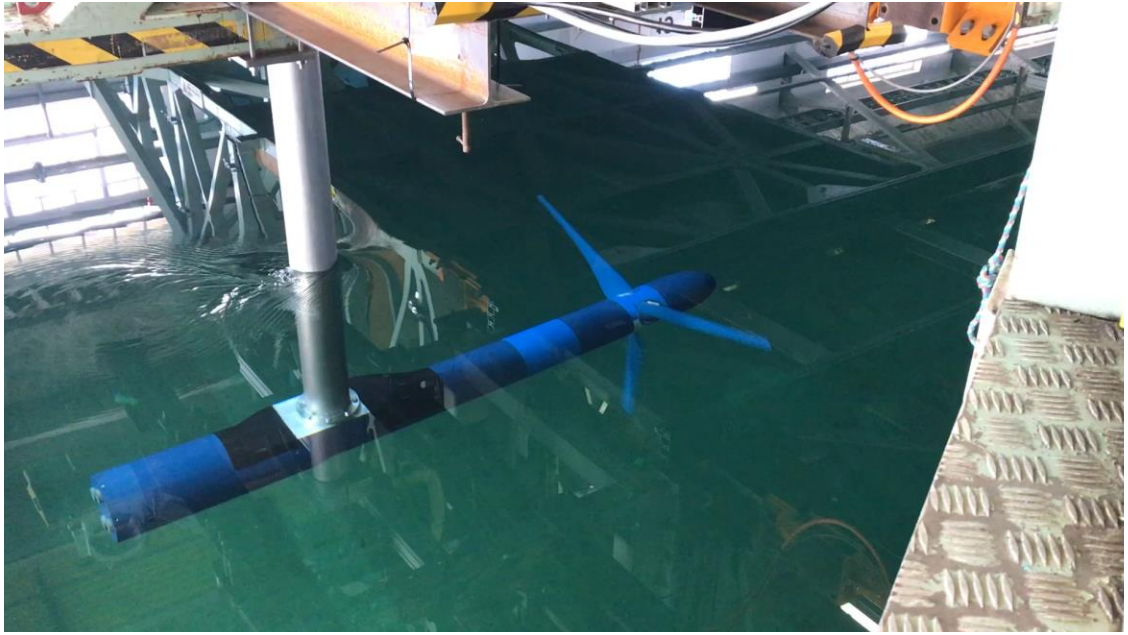
April 2022 Experimental Campaign

- 3D printed shrouding around the hub, Torque and Thrust Transducer and tower joint
- Adjustable depth using A-frame mounted to towing carriage
- All signals passed back through tower during testing



April 2022 Experimental Campaign

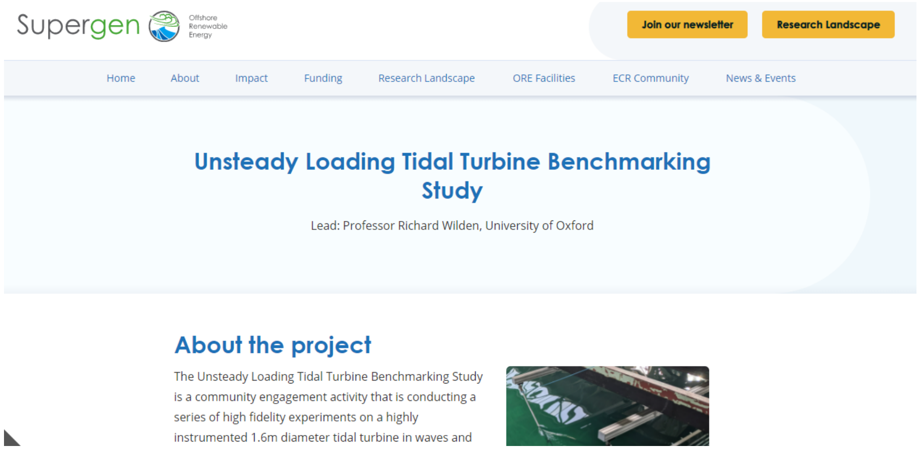
- Yaw adjustment possible in future tests
- Tower stiffened in streamwise direction additional bracket to reduce rotor motion



How to Participate

- Over 60 registered participants with modelling methodologies ranging from BEM, Lattice Boltzmann, vortex lattice, to blade resolved CFD

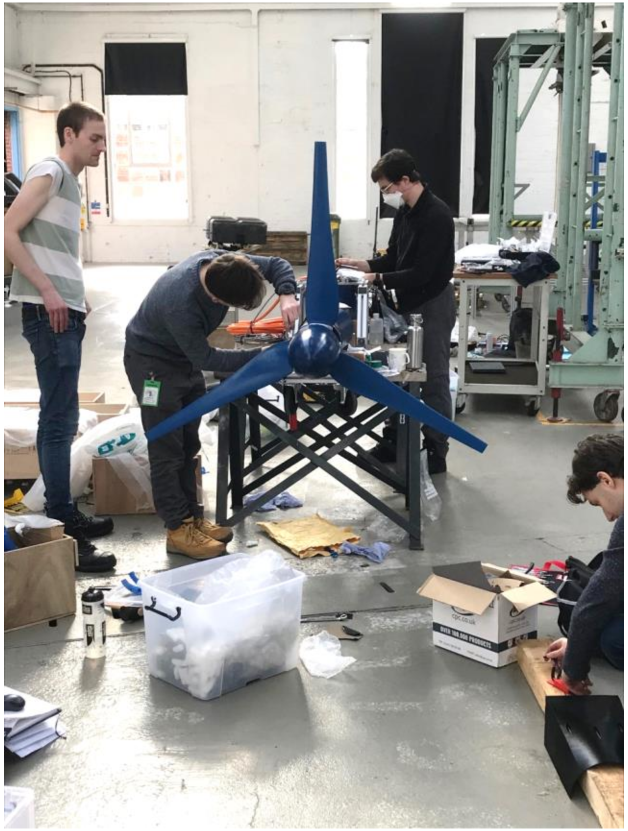
URL: https://supergen-ore.net/projects/tidal-turbine-benchmarking



1. Download **geometry data and test conditions** from the repository linked on the Supergen website
2. Perform blind predictions
3. Download example data **submission file** and submission data formatting guide from the repository linked on the Supergen website
4. Upload data in specified formatted **before Monday 5th September**

Provided Data / 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
  - Flow data from turbulence grid characterisation
  - Measured turbulence quantities and spectra



Benchmarking Test Cases

- The table below illustrates all the steady conditions tested during the April campaign
- Depending on the modelling methodology simulation of more or less cases may be possible
- The **yellow** cases are the priority cases that should be attempted by all simulation methodologies

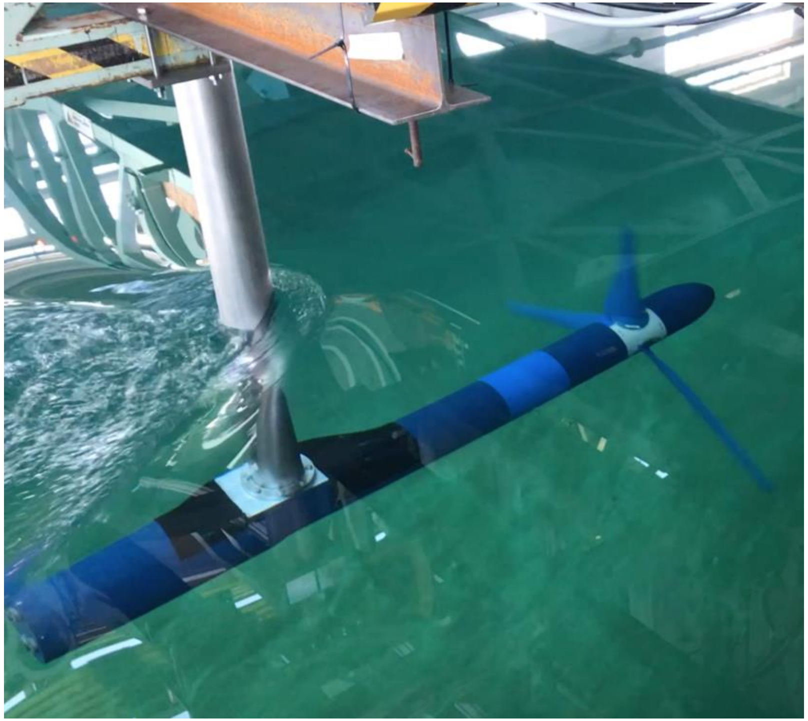
Clean Benchmarking Cases			
Case	Flow Velocity [m/s]	RPM	TSR
Clean 1	1.0	48	4.02
Clean 2	1.0	54	4.52
Clean 3	1.0	60	5.03
Clean 4	1.0	64	5.36
Clean 5	1.0	66	5.53
Clean 6	1.0	69	5.78
Clean 7	1.0	72	6.03
Clean 8	1.0	78	6.53
Clean 9	1.0	80	6.70
Clean 10	1.0	84	7.04
Clean 11	1.0	86	7.20
Clean 12	1.0	90	7.54
Clean 13	1.0	94	7.87

Turbulent Benchmarking Cases				
Case	Flow Velocity [m/s]	Turbulence Intensity [%]	RPM	TSR
Grid 1	0.9207	3.1	43	3.91
Grid 2	0.9207	3.1	49	4.46
Grid 3	0.9207	3.1	54	4.91
Grid 4	0.9207	3.1	59	5.37
Grid 5	0.9207	3.1	62	5.64
Grid 6	0.9207	3.1	64	5.82
Grid 7	0.9207	3.1	68	6.19
Grid 8	0.9207	3.1	70	6.37
Grid 9	0.9207	3.1	76	6.92
Grid 10	0.9207	3.1	81	7.37
Grid 11	0.9207	3.1	85	7.73

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



Questions?