User Project: Dynamic Loading of Tidal Turbine Arrays

Project Acronym: DyLoTTA

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ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

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Disclaimer

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1 Introduction & Background

1.1 Introduction

Knowledge of the loading patterns associated with dynamic flows is needed to understand Tidal Stream Turbine (TST) array performance, fatigue life and reliability in order to drive the industry towards commercially viability. The introduction of unsteady flow (wave and turbulence) has been shown to alter the average power produced and the loading on the turbine. The systematic fundamental study proposed in this application is required to fully understand the dynamic loading of a single TST before studying array effects. This characterisation of the loading regimes faced by a single turbine is essential in validating early stage simulations and for making comparisons between the loading of singular and array mounted TSTs.

Numerical modelling also shows loadings become increasingly asymmetric within unsteady flows. This dynamic loading will be compounded in an array by the wake and potential focusing effects of upstream and lateral turbines. The interaction between the site conditions and array formation is not fully understood but such knowledge is required to ensure the survivability of the devices in such a harsh environment.

Dynamic Loading of Tidal Stream Turbines (DyLoTTA) is a collaborative British Research Council project between Cardiff University and the University of Strathclyde as well as further international and industrial collaborators. The Dylotta project aims to generate quality data sets relating to turbine operation under realistic flow conditions generated via the combination of wave, turbulence and turbine interaction effects. Fitting into a process of sequential inclusion of flow artefacts, this stage of testing was undertaken to provide high quality data relating to a single turbine under well prescribed wave conditions with minimal turbulence effects.

This report presents an overview of the activities associated with MARINET 2 access to the CNR-INSEAN wave towing tank facility for wave and current testing of a 0.9 m diameter horizontal axis tidal turbine (HATT) model.

Previous evidence [Ordonez-Sanchez et al, 2016] has demonstrated the effects of using control strategies on the loading fluctuations that the turbine is subjected to. Therefore, the testing undertaken during Marinet 2 aims to study the effects of normal, extreme and irregular waves on dynamic turbine loads under the speed and torque control types. This was done by initially studying the turbine characteristics under no wave tow tests for both speed and torque control operation. Secondly, a representative medium monotonic wave was generated of 0.1 m amplitude and 1.44 s period – again under torque and speed control setups. Next the turbine was tested under extreme wave conditions of representative specific of 0.2 m amplitude and 2.0s wave period. Lastly, the turbine was subjected to irregular waves generated in a manner which adhered to the JONSWAP wave spectrum with a significant wave height of 0.1 m and period of 1.44 s.

It was found that generally under the no wave conditions similar thrust loading and power generation were found for both the speed and torque control types. Under the wave cases a larger fluctuation in torque was observed for the speed control case. However, a larger fluctuation in rotor thrust loading was measured for the torque control cases. In terms of the extreme wave case, power fluctuations of up to 52 % of the mean power output were found for the speed control case, this compared with maximum power fluctuations of 33 % measured for the torque control case. Similarly, for the extreme wave case, 18 % and 40% rotor thrust fluctuations were observed, relative to the mean thrust, for the speed and torque control cases respectively.

1.2 Development So Far

1.2.1 Stage Gate Progress

The access afforded by MARINET 2 allowed members of the DyLoTTA project to achieve a number of the aims DyLoTTA project. Below and overview of the main deliverables associated with the DyLoTTA project are outlined.

Complete: ✓ Started: ⓘ Not Started: ➲

Table 1: Table showing the deliverables and progress made in the DyLoTTA project as of March 2018.

	Deliverable	Status
1	Collection, organisation and cleaning of detailed Site Data	ⓘ
2	Three instrumented TSTs capable of deployment as an integrated array.	ⓘ
3	Specification of the TST array condition monitoring and control system.	ⓘ
4	Deployment of the TST array condition monitoring and control system	➲
5	Specification and testing of diagnostic/prognostic CM tool for model and full scale TST	➲
6	Lift and drag data for BEMT model	ⓘ
7	A defined set of inlet conditions to input into the CFD and coupled FSI models	ⓘ
8	TST array performance and load characteristics when operating over a range of dynamic sea states	ⓘ
9	Data to validate the numerical models	ⓘ
10	Data for Condition Monitoring Specification	ⓘ
11	Data for Life Fatigue Analysis	ⓘ
12	A series of three TST array configurations.	➲
13	Validated CFD models of the TST arrays used in the tow tank experiments	➲
14	FEA models of experimental TSTs for structural loading	➲
15	One-way coupled FSI models of the TSTs	➲
16	Model validated against data sets from single device tank testing.	✓
17	Proven full scale TST CFD model.	➲
18	FSI model of full scale TST.	➲
19	CFD models of turbine arrays	ⓘ
20	Data for Life Fatigue Analysis	ⓘ
21	Data for comparison with BEMT models	ⓘ
22	Specification of a Life Fatigue Analysis of a TST	➲
23	New array layouts to mitigate the negative impacts of extreme sea conditions	ⓘ
24	Identification of the factors influencing the LCOE for the identified array configurations and quantification of the lowest LCOE.	ⓘ

1.2.2 Plan for This Access

The objects for this MARINET 2 project were developed to broadly support the research activities on-going as part of the aforementioned DyLoTTA project. Specifically the goals of this project were:

- To commission and test the design of a 0.9 m diameter scale model TST. The device was developed to facilitate research objective and aid in the generation of detailed data sets relating to scale TST testing under a variety of wave, turbulent and device impacted on-coming flow scenarios.
- To characterise the scale model TST under steady flow conditions with minimal turbulence effects. This was under taken to both validate early CFD models of the scale model HATT and to provide a performance benchmark with which testing with waves, turbulence and multiple devices could be compared.
- To generate data sets showing the turbine response to a number of surface wave cases for both speed and torque control. The data sets will provide information for the validation of CFD Volume Fraction (volume of fluid) models. Furthermore, the data sets can be used to study turbine response to extreme wave conditions under a variety of control scenarios.

- To provide data on the response of a single turbine to wave conditions as a benchmark before progressing to the testing of TST arrays.

The DyLoTTA team design and built the 0.9 m diameter HATT prior to testing. The experimental design was generated and discussed with the facility managers. Aspects of power cable requirements, lifting and installation requirements were also discussed. The torque and thrust transducer was calibrated prior to access following the BSI standard. Due to delays in the manufacturing of the turbine hub by contractors water proofing of the hub was undertaken 24 hours prior to departure for the CNR-INSEAN facility – this meant that the blade load measurement transducers required calibration post-access. Data capture and turbine control procedures were developed and tested as far as practicable on the run up to access.

2 Outline of Work Carried Out

2.1 Model

The 1/20th scale model turbine used in the testing was designed and produced in a collaborative effort between Cardiff University and the University of Strathclyde. Figure 1 shows the 1/20th Scale HATT; Figure 2 shows the original Solidworks model of the turbine. The HATT houses three adapted Wortman FX 63-137 blades and is controlled via a direct drive permanent magnet synchronous machine (PMSM). The turbine is instrumented with an encoder, blade moment loading transducers and a combined rotor thrust and torque transducer. As well as quantities measured via the fitted instrumentation suite, PMSM quantities such a torque generating current, DC bus power and motor temperature are also recorded. Lastly, the turbine can be operated under a variety of control implementations – in this case a comparison was made between set point speed and torque control.

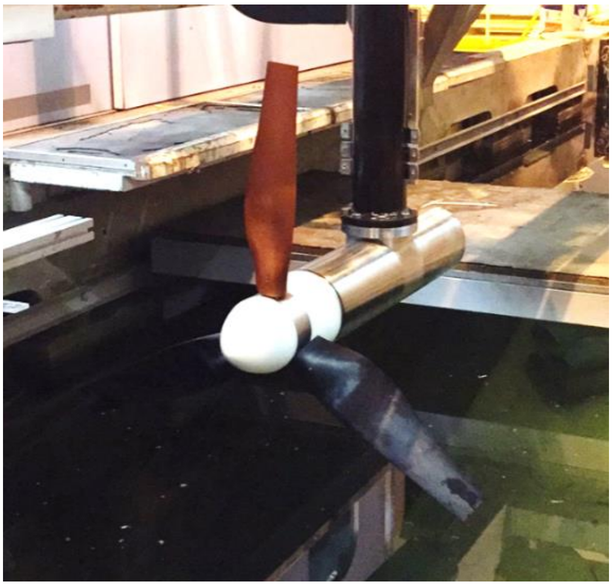

Figure 1: Picture of the assembled 0.9 m HATT.

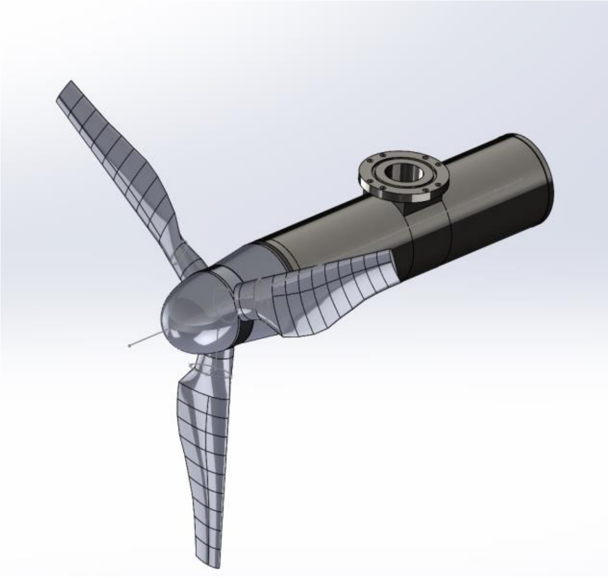

Figure 2: Solidworks render of the 0.9 m diameter HATT design.

2.2 Set-up

The turbine was delivered to CNR-INSEAN on the 10th of November 2017. The apparatus was unloaded and checks made on the Friday afternoon. Upon checking the turbine drive shaft, an unacceptable albeit small eccentricity of the drive shaft was found. This was due to bend in the drive shaft which had most likely occurred during loading or transit. On the Monday morning technicians at INSEAN help rectify the problem by removing and straightening the bent shaft. In the meantime, other staff at INSEAN installed the turbine drive cabinet on the tow carriage. On the

Tuesday the turbine was re-assembled and the instrumentation checks made. It was found that a wiring error had occurred and this was quickly check and amended. Upon confirming the correct operation of the instrumentation systems, the stanchion was mounted on the tow carriage. The turbine blades were mounted and set to the correct pitch angle. Then, the turbine was mounted onto the stanchion and the whole assembly bolted into place. Lastly, the pitot, ultrasonic and capacitance wave probes were all installed ready for testing to commence on the Thursday. Lastly, an electromagnetic current meter was installed – the hardware was used to determine its suitability for use throughout the testing phases proposed as part of the DyLoTTA project.

Figure 3: INSEAN staff removing material from the turbine drive shaft to rectify eccentricity.

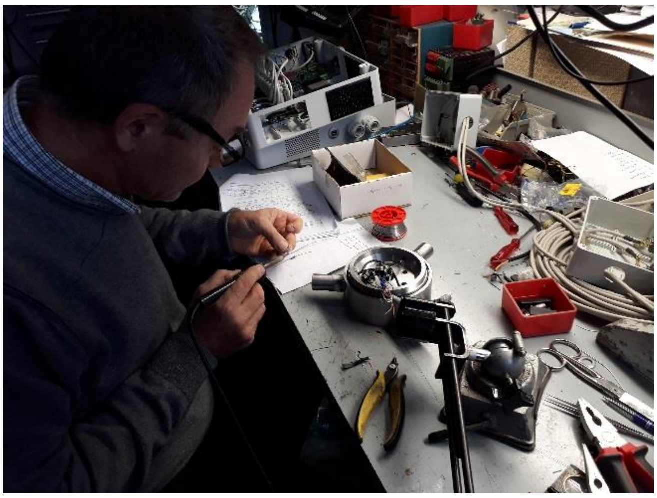

Figure 4: INSEAN technician re-soldering loose connection.

Figure 5: Mounting the blades and setting pitch angles.

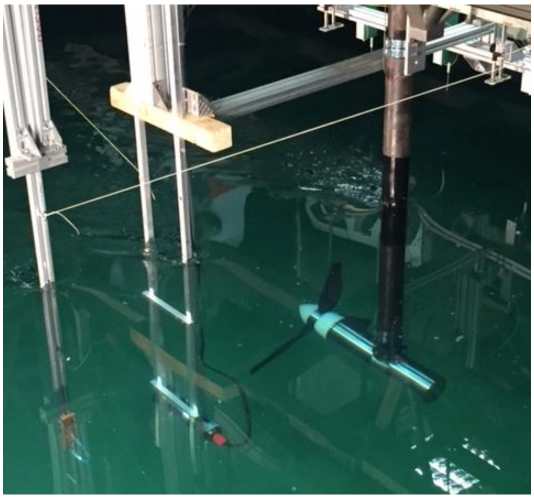

Figure 6: The installed turbine.

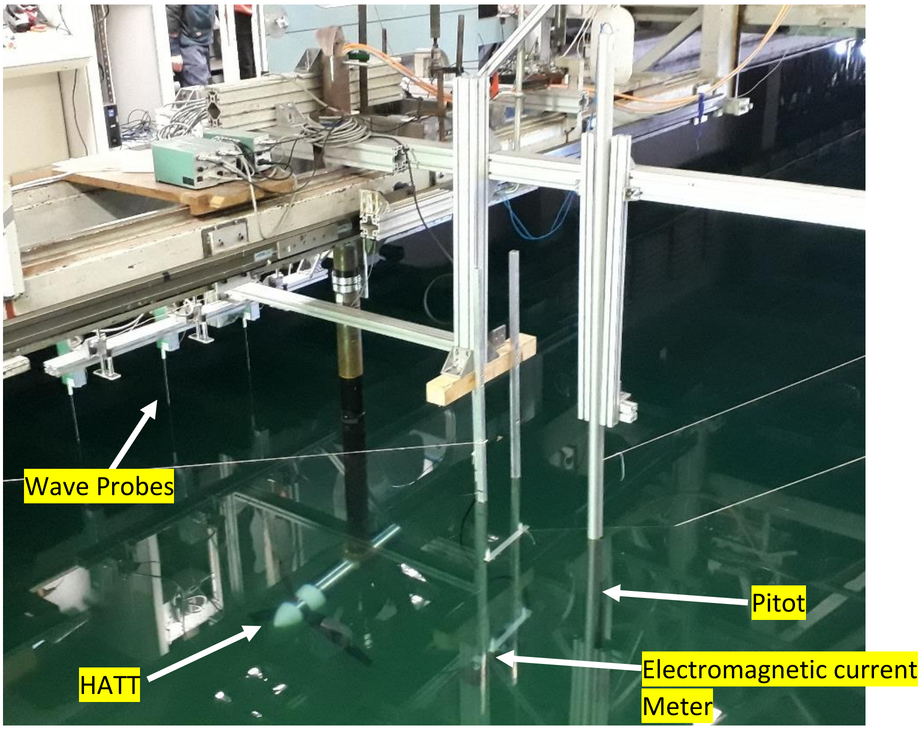

Figure 7: Overview of the test setup at INSEAN

2.3 Tests

The testing was scheduled with the facility manager to be between the 12th and 24st of November 2017 including commissioning and decommissioning time. Due to the some of the unforeseen difficulties with the turbine setup, testing commenced on Thursday 16th. In spite of the difficulties with the setup it was clear that the fundamentals of the test plan proposed could be completed in the allotted time – that is the test plan up to and included both normal and extreme waves. This additional time facilitated additional wave testing for the extreme and normal cases, as well as irregular wave testing. Below an overview of the testing activities undertaken is presented.

2.1.2 Week 1

Table 2: Table showing the testing activities undertaken in week 1.

Day	AM	PM
Monday	Turbine Instrumentation tests and installation setup	Turbine Instrumentation tests and installation setup
Tuesday	Instrumentation corrections: Lose connections.	Turbine Final Setup: Blade pitch angle setting etc.
Wednesday	Turbine Installation	Software checks and water proofing checks
Thursday	Turbine Characterisation Tests – Speed Control.	Turbine Characterisation Tests - Speed Control.
Friday	Turbine Characterisation Tests – Torque Control.	Turbine Characterisation Tests – Torque Control.

2.1.3 Week 2

Table 3: Table outlining the testing activities undertaken in week 2.

Day	AM	PM
Monday	Extreme Wave Case: Speed Control	Extreme Wave Case: Speed Control
Tuesday	Extreme Wave Case: Torque Control	Moderate Wave Case: Speed Control
Wednesday	Moderate Wave Case: Speed Control	Moderate Wave Case: Torque Control
Thursday	Turbine Removal and Checks	Characterisation Repeats
Friday	Irregular Waves. Torque and Speed Control	Decommissioning

2.1.4 Wave Cases:

Extreme Wave	Amplitude = 0.2 m, Period = 2.0 s, U = 1 m/s
Moderate Wave	Amplitude = 0.1m, Period = 1.44 s, U = 1 m/s
Irregular Wave	JONSWAP Significant Wave Height = 0.2 m, Peak Period = 1.44 s, U = 1 m/s

2.4 Results

A brief exploration of the results has been provided to give the reader an insight into the collected data sets and the initial findings of the project. The results are presented in terms of non-dimensional parameters which are defined as follows:

$$C_p = \frac{\omega \cdot Torque}{\frac{1}{2}\rho A v^3} \qquad (1)$$

$$C_t = \frac{Thrust}{\frac{1}{2}\rho A v^2} \qquad (2)$$

$$C_\theta = \frac{Torque}{\frac{1}{2}\rho A R v^2} \qquad (3)$$

$$\lambda = \frac{\omega R}{v} \qquad (4)$$

Within the set of equations above the following nomenclature can be applied. The written quantities, $Thrust$ *and* $Torque$ refer to measured data via the rotor Thrust transducer and PMSM. ρ is the fluid density in kg/m^3, A is the turbine rotor swept area in m^2 and R is the turbine radius in meters. v is the fluid velocity measured via the pitot tube or tow carriage velocity in the wave and non-wave cases respectively – units are ms^{-1}. Lastly, ω is the rotational velocity of the model turbine, measure via the encoder in $rads^{-1}$.

Power curves showing the non-dimensional power coefficient, as defined in (1), for a number of the test cases are shown. Figure 8 to Figure 10 show the power coefficients calculated for the no-wave case and extreme wave case, on each figure the results of the speed and toque control tests are shown in each. The error bars show two times the standard deviation observed. A peak C_p value of approximately 0.42 was found for both the no-wave and extreme wave case.

Figure 11 to Figure 13 show the non-dimensional thrust coefficients, as defined in (2), for each both the non-wave case and the extreme wave case – again Figure 13 shows the instantaneous thrust coefficient. The instantaneous non-dimensional values were calculated for each measured sample point using equations (1) to (3). The error bars show two times the standard deviation observed. A peak C_t value of approximately 0.85 was found for no-wave case whereas a peak of 0.80 was found for the extreme wave case. As expected a large fluctuation in thrust coefficient was observed for the extreme wave case.

Figure 14 to Figure 16 show the non-dimensional torque coefficients, as defined in (3), for each both the non-wave case and the extreme wave case –Figure 13 Figure 16 shows the instantaneous thrust coefficient. A peak C_θ value of approximately 0.143 was found for both the no wave and extreme wave case.

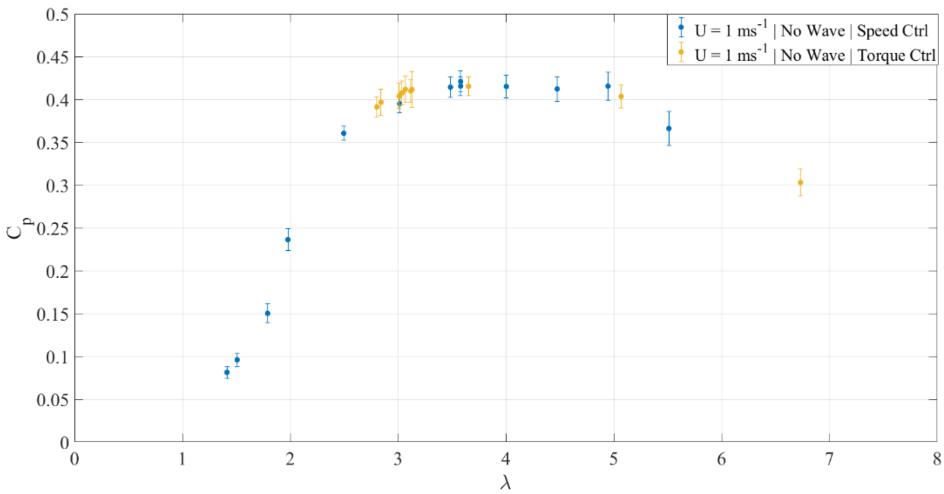

Figure 8: Cp vs λ for the non-wave, steady flow tests for both speed and torque control cases.

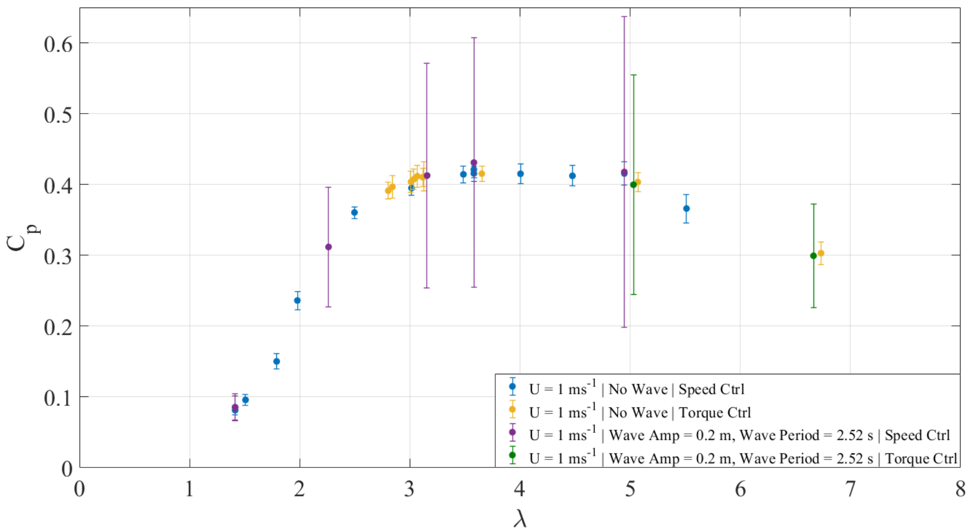

Figure 9: Cp vs λ for the steady flow and extreme wave tests for both speed and torque control cases.

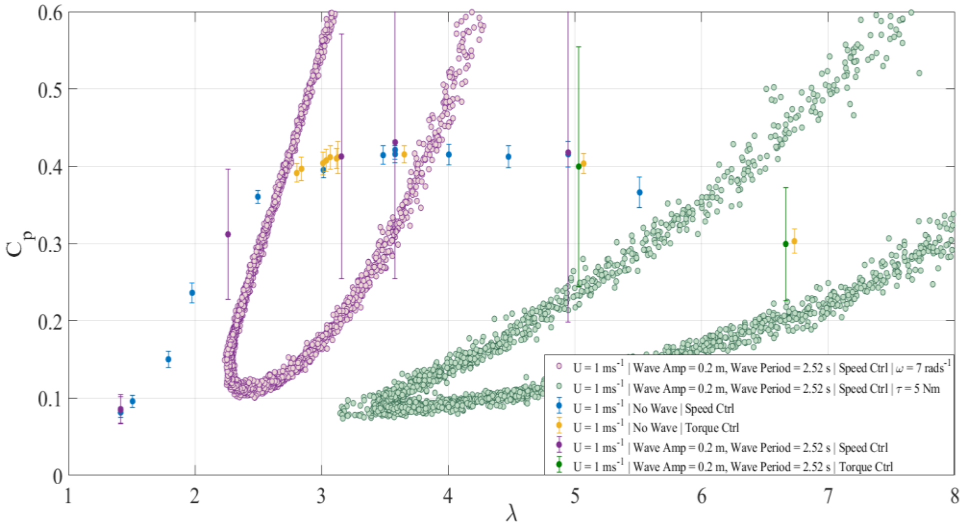

Figure 10: Cp vs λ for the steady flow and extreme wave for both speed and torque control cases. Instantaneous non-dimensional values have been included.

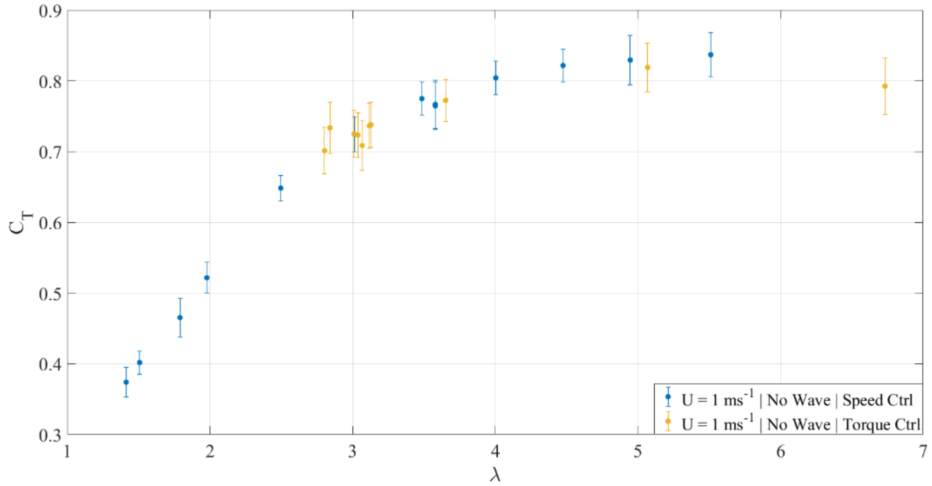

Figure 11: Ct vs λ for the non-wave, steady flow tests for both speed and torque control cases.

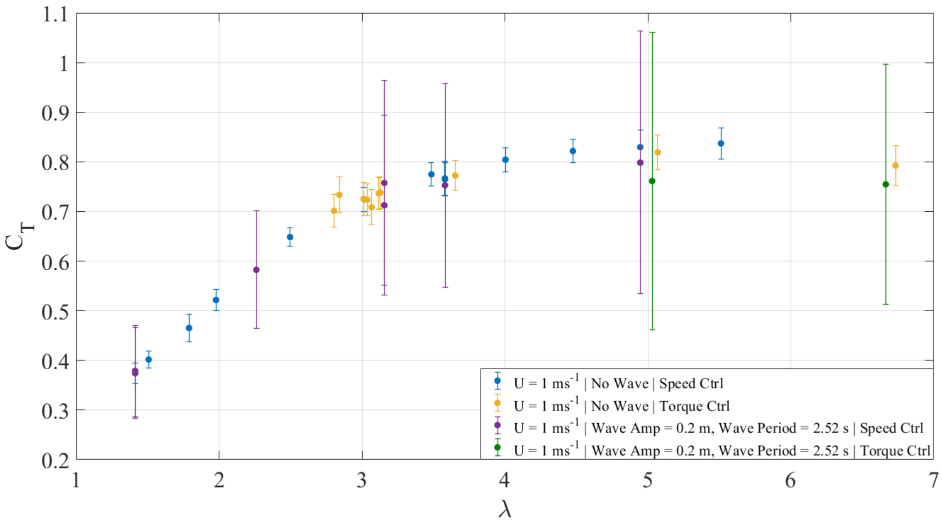

Figure 12: Ct vs λ for the steady flow and extreme wave tests for both speed and torque control cases.

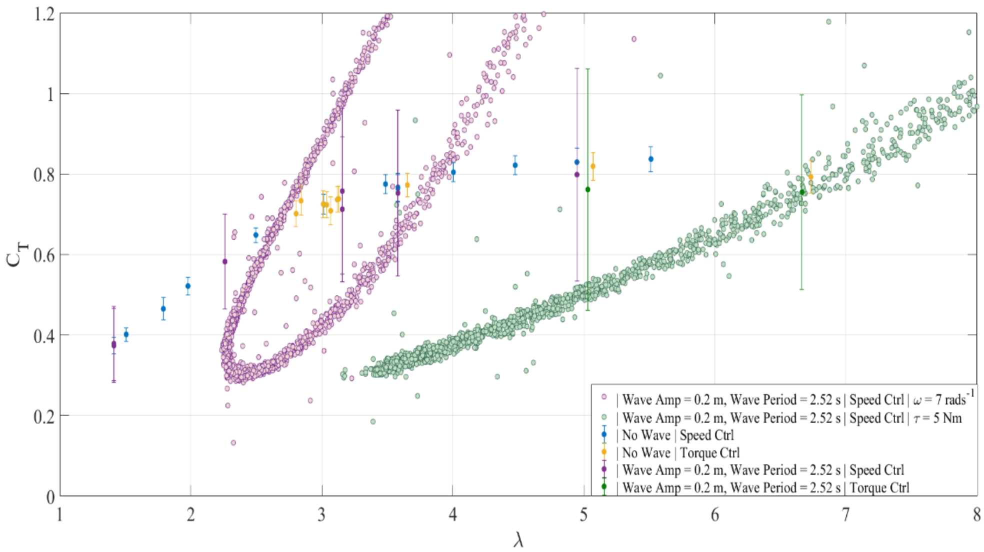

Figure 13: Ct vs λ for the steady flow and extreme wave tests for both speed and torque control cases. Instantaneous non-dimensional values have been included.

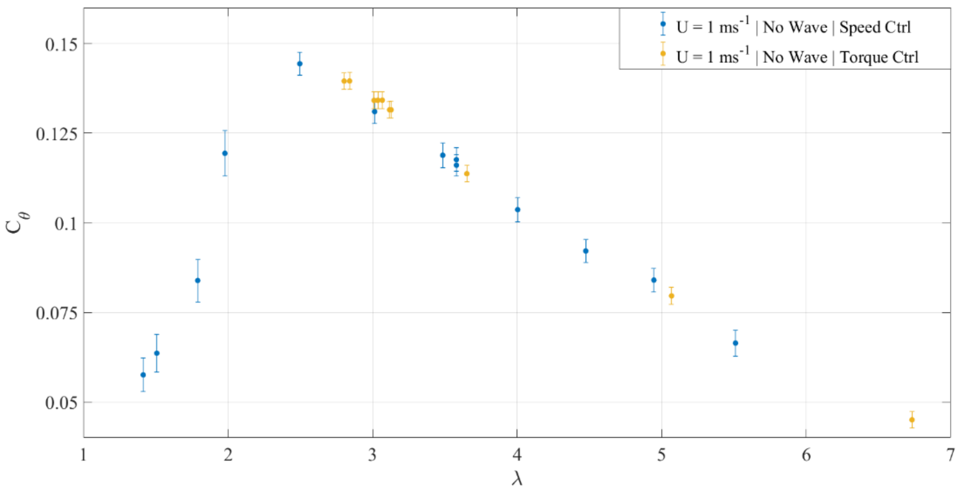

Figure 14: C_θ vs λ for the non-wave, steady flow tests for both speed and torque control cases.

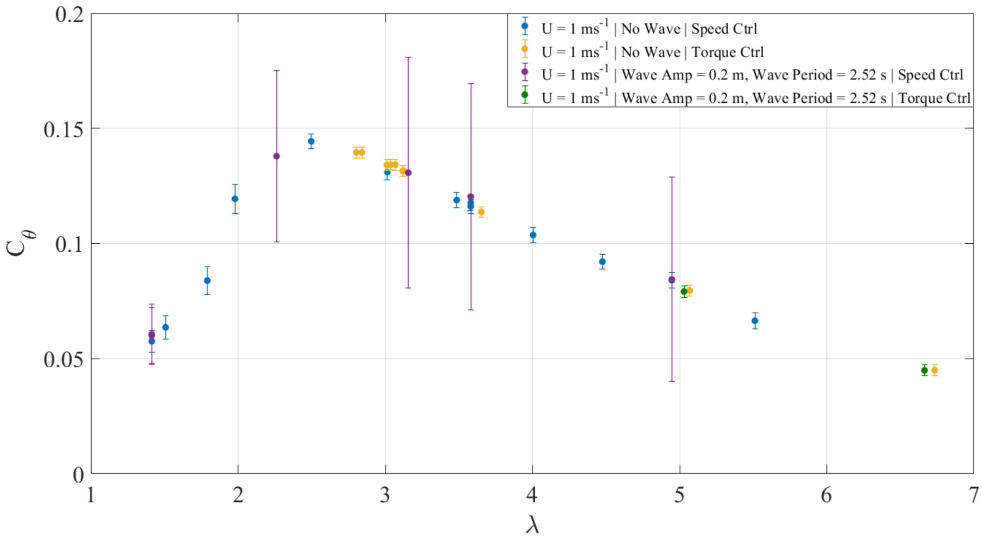

Figure 15: C_θ vs λ for the steady flow and extreme wave tests for both speed and torque control cases.

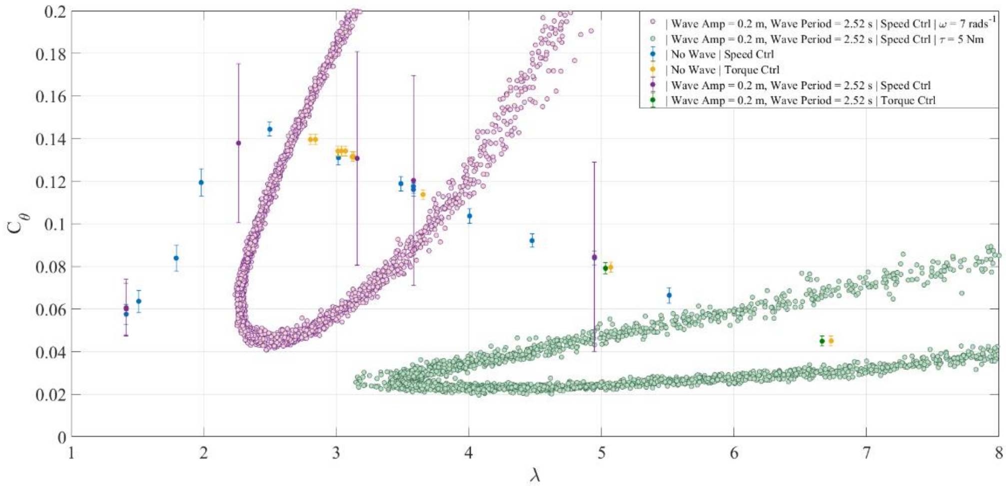

Figure 16: C_θ vs λ for the steady flow and extreme wave flow tests for both speed and torque control cases. Instantaneous non-dimensional values have been included.

2.5 Analysis & Conclusions

2.1.5 Analysis

Whilst analysis of the results are still on-going a discussion of the results presented above is given. Firstly, it can be observed in Figure 8, Figure 11 and Figure 14 the test setup and instrumentation resulted in a high level of repeatability in terms of non-dimensional power, thrust and torque coefficients. Specifically, repeat test for $\lambda \approx 3.5$ gave mean results within 2 % for power and torque coefficients and 1% for thrust coefficient.

As expected large fluctuations in power, thrust and torque coefficients were observed for the extreme wave case shown. With reference to Figure 9Figure 11 Figure 12 and Figure 15 the extent of the wave induced fluctuations can be observed – whilst large fluctuations in non-dimensional coefficients were exhibited, generally similar mean non-dimensional values were observed. Exceptions to the invariability of the mean non-dimensional coefficients can be seen in Figure 12. Here, for λ values above 4, lower thrust coefficients were observed for the extreme wave case relative to the steady flow case. Furthermore and as expected, Figure 15 shows minimal induced fluctuations in the torque coefficient for the constant torque control case.

Comparing the effects of set-point speed and torque control, Figure 8, Figure 11 and Figure 14 show that minimal difference in mean and standard deviations in non-dimensional parameters were found for the differing control strategies. However and with reference to Figure 10, Figure 13 and Figure 16, it can be observed that significant impacts on induced fluctuations in power, thrust and torque coefficients were recorded. Specifically, power coefficient fluctuations of 52 % and 18 % were observed for the speed and torque cases, respectively. Alternatively, wave induced thrust coefficient fluctuations of 33 % and 40 % were observed for speed and torque control cases, respectively. Figure 10, Figure 13 and Figure 16, show the instantaneous values of the λ, non-dimensional coefficient pairs for each measurement sample taken. It can be seen that the waves induce large fluctuations in the fluid velocity impacting the turbine. In the speed control case this leads to some scatter in the λ-values observed. In the torque control cases large scatter of the λ values observed can be attributed to the fluctuating nature of both the on-coming fluid velocity and by association the turbine rotational velocity. The large scatter in non-dimensional values suggests that non-dimensional values maybe of limited use when looking at wave induced effects. However, at this stage it is considered that the scatter in the data could be attributed to a phasing mismatch between the measured flow data and the turbine power, thrust and torque measurements.

2.1.6 Key findings:

- The test setup and in particular the scale model instrumentation gave good repeatability in the results.
- Under the extreme wave case induce power fluctuations of up to 52% and 18% were observed for the speed control and torque control cases, respectively.
- Under the extreme wave case induce thrust fluctuations of up to 33% and 40% were observed for the speed control and torque control cases, respectively.
- Large fluctuations in non-dimensional parameters, as defined in equations (1) through (4), are likely to mean that non-dimensional parameters may be difficult to interpret under wave conditions – although analysis is proceeding to define the extent of this finding.

3 Main Learning Outcomes

3.1 Progress Made

3.1.1 Progress Made: For This User-Group or Technology

The progress made in terms of the undertaken MARINET 2 project is as follows:

- Completion design, manufacture and commissioning of a 1/20th scale model TST.
- Characterisation of the model turbine.
- Generation of a data set relating to scale model TST operation under extreme, normal and irregular wave climates. The data sets relate to both set-point speed and torque control of TSTs.
- Generation of data sets for CFD model validation.
- Initial data review has been completed and analysis is on-going.

3.1.2 Progress Made: For Marine Renewable Energy Industry

- Generation of a data set relating to HATT operation in wave conditions, the data set can be used for validation of differing modelling approaches to understanding HATT operation in wave climates.
- Data relating to the dynamic loading of HATTs under differing control strategies gathered, leading to improved understanding of HATT control in wave climates.
- Creation of a benchmark dataset for research activities in DyLoTTA which will eventually yield quantification and dynamic loading scenarios generated via interaction between devices, surface waves and turbulence.

4 Further Information

4.1 Scientific Publications

The following abstracts based on the testing have been submitted to the Asian Wave and Tidal Energy Conference by researchers at Cardiff University and the University of Strathclyde:

- Design Process for a Scale Horizontal Axis Tidal Turbine Blade.
- Wave-current numerical modelling using Stokes 2nd Order and Linear Wave Theory.
- Laboratory study of tidal turbine performance in irregular waves.
- The Development and Testing of a Lab-Scale Tidal Stream Turbine for the Study of Dynamic Device Loading

A journal paper based on the testing campaign is current being drafted. (April 2018)

4.2 References

Ordonez Sanchez, S, Porter, K, Frost, C, Allmark, M, Johnstone, C & O'Doherty, T 2016, 'Effects of extreme wave-current interactions on the performance of tidal stream turbines' Paper presented at 3rd Asian Wave and Tidal Energy Conference, Singapore, Singapore, 24/10/16 - 28/10/16, .

4.3 Website & Social Media

Website:

CMERG - http://cmerg.engineering.cf.ac.uk/

CNR INSEAN - http://www.insean.cnr.it/content/cnr-insean

DyLoTTA - http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/N020782/1

4.4 Acknowledgments

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