

Infrastructure Access Report

Infrastructure: UNIFI-CRIACIV Wave-Current Flume

User-Project: TEDSSWIP

Tidal Energy Device: Support Structure Wake Impact on Performance

[Optional: Insert user or company name(s)]



Status: Final
Version: 02
Date: 16-Oct-2014



ABOUT MARINET



























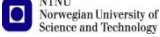

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The aim of the initiative is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

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	<p>Belgium 1-Tech (1_TECH)</p>		

DOCUMENT INFORMATION

Title	Tidal Energy Device: Support Structure Wake Impact on Performance
Distribution	Public
Document Reference	MARINET-TA1-TEDSSWIP
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Infrastructure Accessed:	UNIFI-CRIACIV Wave-Current Flume
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REVISION HISTORY

Rev.	Date	Description	Prepared by (Name)	Approved By Infrastructure Manager	Status (Draft/Final)
01	15/10/14		Stuart Walker		Draft
02	16/10/14		Stuart Walker	Lorenzo Cappiatti	Final

ABOUT THIS REPORT

One of the requirements of the EC in enabling a user group to benefit from free-of-charge access to an infrastructure is that the user group must be entitled to disseminate the foreground (information and results) that they have generated under the project in order to progress the state-of-the-art of the sector. Notwithstanding this, the EC also state that dissemination activities shall be compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the owner(s) of the foreground.

The aim of this report is therefore to meet the first requirement of publicly disseminating the knowledge generated through this MARINET infrastructure access project in an accessible format in order to:

- progress the state-of-the-art
- publicise resulting progress made for the technology/industry
- provide evidence of progress made along the Structured Development Plan
- provide due diligence material for potential future investment and financing
- share lessons learned
- avoid potential future replication by others
- provide opportunities for future collaboration
- etc.

In some cases, the user group may wish to protect some of this information which they deem commercially sensitive, and so may choose to present results in a normalised (non-dimensional) format or withhold certain design data – this is acceptable and allowed for in the second requirement outlined above.

ACKNOWLEDGEMENT

The work described in this publication has received support from MARINET, a European Community - Research Infrastructure Action under the FP7 “Capacities” Specific Programme.

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EXECUTIVE SUMMARY

The work described herein aimed to generate experimental data on the relative performance of a tidal stream turbine mounted on four support structure designs. By using the same turbine design and flow conditions in each case, the project aimed to isolate the relative effect of support structure design on turbine performance. The project was carried out in the Wave-current flume at the Department of Civil and Environmental Engineering of the University of Florence, as part of a project based at the University of Sheffield and co-funded by Marine Renewables Infrastructure Network [1].

The support structure designs were chosen based on those proposed by device manufacturers, incorporating a vertical cylinder, a tripod, an angled cylinder design and a cable moored design. Models were tested at approximately 1:72 of real scale, with a base to turbine tip height of 393.5mm and a blade diameter of 250mm. Support structure designs were tested at under otherwise identical conditions at tip speed ratios between 2 and 6. Turbine models were driven, and rotational speed and blade power generation were measured. Downstream flow conditions were also monitored using acoustic and ultrasonic equipment.

Optimal power coefficients were found to occur at tip speed ratios between 3 and 4. The tripod support structure design appeared to operate more effectively in low tip speed ratio conditions, whereas the angled and cylinder designs were found to achieve their optimum power coefficient in higher speed cases. The cable moored system appeared to operate very effectively at low speed conditions, but its performance was lower than the other designs in high-TSR cases.

Subsequent and ongoing analysis has suggested a correlation in the measured data between turbine performance and turbulence intensity in the near downstream region, with a high turbulence intensity leading to a reduction in the power generated by the turbine. It is possible that turbulence and flow structures generated by the support structure have a significant effect on the blades, and thus the power generating potential and energy yield of a turbine.

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1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

In recent years the development of tidal stream turbines has been rapid and great advances have been made. However, work has focused on the design of the active components of a single device, such as blades and electrical systems. In order to design and install effective arrays of tidal turbines, further work is needed to understand the impact of an upstream device on the performance of downstream devices, which are required to work in the turbulent wake of upstream machines. Work in this area has been carried out in The University of Sheffield Sediment Transport laboratory for the past three years [2], and has focused on the impact of the support structure on wake generation, and subsequently device performance. Results indicate that the support structure does play a significant role in device wake generation, and that the presence and position of an upstream device can dramatically affect the performance of a downstream device.

Due to the infancy of the technology, there currently exist a wide range of tidal turbine designs proposed by companies around the world. Despite this, horizontal axis turbines are by far the most prevalent design, and are favoured by most commercial developers. Indeed, all the currently proposed arrays intend to use horizontal axis tidal turbines. Within the field of horizontal axis tidal stream turbines, there are numerous further layers of design variation, of which support structure design is one.

The focus of the present work is the assessment of the wake generated by the support structure of a tidal stream turbine. In order to ascertain the most likely support structure designs to be installed as part of a commercial array a literature review was conducted to discover the tidal stream turbine designs which are the closest to commercial deployment. Device designs were assessed by the duration of full-scale commercial testing which had been successfully completed. Previous assessments of the commercial readiness of various turbine designs were also consulted [3-4]. Based on the findings of this assessment, four designs of support structure were defined. Scale models of these designs were subsequently tested during the TEDSSWIP project, using the UNIFI-CRIACIV Wave-Current Flume. The final models as tested during the TEDSSWIP project are illustrated below.

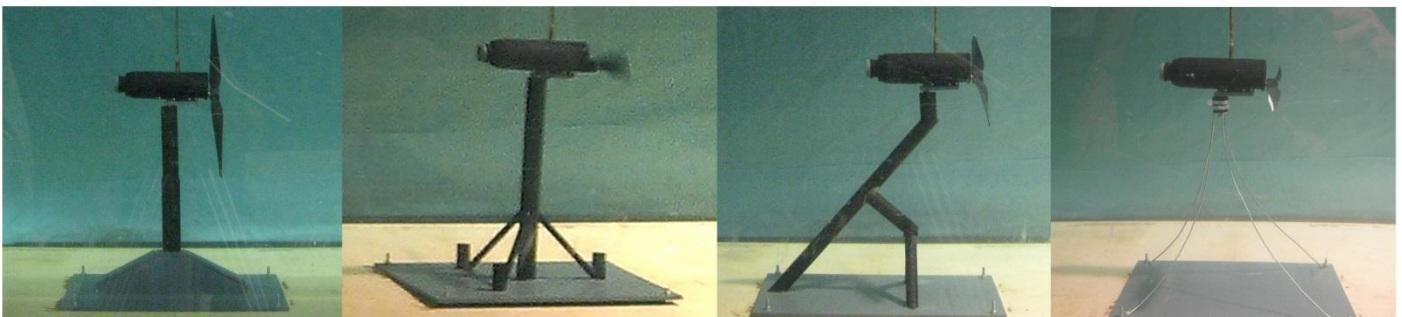


Figure 1 – Turbine mounted on four support structure designs as tested during TEDSSWIP project

1.2 DEVELOPMENT SO FAR

1.2.1 Stage Gate Progress

Previously completed: ✓
 Planned for this project: ➡

STAGE GATE CRITERIA	Status
Stage 1 – Initial model testing (Scale 1:180)	
• To illustrate device wake (dye injection)	✓
• To simulate velocity deficit using actuator disks	✓

STAGE GATE CRITERIA	Status
Stage 2 – Single device simple support structure testing (Scale 1:144)	
• To investigate the effect of the support structure/blade separation distance on the device wake	✓
• To investigate the effect of support structure diameter on the device wake	✓
• To investigate the effect of support structure diameter on the torque output of a device	✓
Stage 3 – Multiple device simple support structure testing (Scale 1:144)	
• To investigate the effect of an upstream turbine on the torque output of a downstream device	✓
• To investigate the effect of an offset upstream turbine on the output of a downstream device by adjusting its lateral position	✓
Stage 4 – Complex support structure testing (Scale 1:72)	
• To investigate the difference in device wake structure for the same turbine installed on four different designs of support structure	↻
• To study device torque output for the same turbine installed on four different designs of support structure	↻

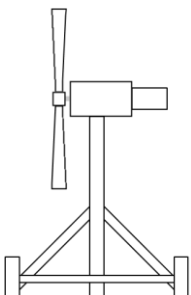
1.2.2 Plan For This Access

The primary aim for this access period was to test scale models of four tidal turbine support structures, in order to understand the difference in the wakes generated by each. The wake generated by the support structure is known to have a significant effect on the wake of the device as a whole, and also can have a significant effect on the performance of a device.

In order to ensure comparative results, the four support structure models were tested using a single design of scale turbine model. A two-blade rotor with a blade diameter of 250mm was used. Base-mounted turbine models (i.e. designs 1, 2 and 3) had a base-to-hub height of 268.5mm. The torque generated by the turbine blades in each case was measured, and thus allow the impact of the support structure on the performance of the turbine to be recorded under a range of flow conditions. The CRIACIV Wave-Current Flume has a width of 800mm, and a water depth of 600mm was used in all cases. A flow discharge rate of 74l/s was used.

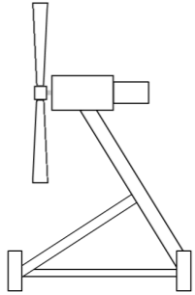
The four tidal turbine support structure models to be tested are described in the following sections. Simple schematic diagrams of the designs are also given.

1.2.2.1 Design 1: Tripod



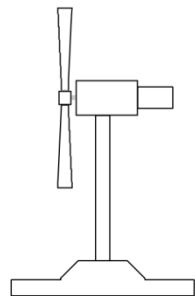
This design is based around a large diameter central post, onto the top of which the turbine is mounted. The lower part of the post is supported by a tripod design with angled supports, on the ends of which are small vertical posts to allow piled foundations to be used.

1.2.2.2 Design 2: Angled post



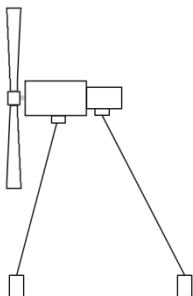
This design is again based on three piled foundations. One piling post is mounted at the rear of the large main support post, which is angled forwards to support the turbine. The lower part of this post is supported by two smaller arms which reach out to the sides to support two more piles.

1.2.2.3 Design 3: Vertical post



The vertical post design is theoretically relatively simple. It differs from designs 1 and 2 in that it is not of entirely tubular construction. The main central post is tubular, but the large base below is of rectangular section, with a higher sectional height at the centre.

1.2.2.4 Design 4: Catenary moored



The final design is a moored turbine design. The turbine is mounted on a system of four cables, two of which are mounted on at the front of the turbine unit, and two to the rear. The turbine unit itself is mounted below a floating pontoon (not shown).

2 OUTLINE OF WORK CARRIED OUT

2.1 SETUP

Prior to commencement of testing, the turbine system, support structure models and instrumentation were installed in the flume. The installation of the turbine models and particularly the location of the turbine and the connection of the turbine drive motor required precise alignment to ensure that no additional loads would be placed on the drive motor. Tests were conducted on each of the four support structure designs consecutively (ie. All tests using support structure 1 were completed before tests on support structure 2 were begun, and so on), in order to minimise the requirement to remove the drive system connection and the universal turbine unit from the support structures.

2.2 MEASUREMENT

2.2.1 Turbine instrumentation

In order to calculate the power generated by the turbine blades, it was first necessary to measure the rotational velocity of the turbine, and the power supplied to the turbine by the drive motor system. This was achieved using an optical encoder mounted on the turbine drive shaft. The power supplied to the turbine drive motor was measured

using a current measurement module, and data from both the instruments was recorded using a LabJack U12 data acquisition module. A recording frequency of 50Hz and a total time of 90 seconds per experiment were used, giving a total of around 4500 data points per test.

2.2.2 Flow measurement equipment

A range of flow measurement equipment was employed during this study. An ultrasonic doppler (UDV) and acoustic doppler velocimeter (ADV) were used to measure flow velocity; a electro-magnetic flow meter was used to measure bulk flow rate; three wave gauges were used to precisely measure water depth; and turbine performance was measured using an optical encoder and power measurement module.

The UDV (Signal Processing DOP1000) was positioned at 1 rotor diameter (250mm) downstream of the turbine blade position, and recorded 75 instantaneous profiles during a 33s recording duration, giving a frequency of 2.27Hz. Each profile contained a vertical plot of the velocity at the vertical centreline of the flume and the 1D downstream position, and was made up of 204 vertical points, at an approximate spacing of 2.9mm. A sample plot is shown in Figure 2.

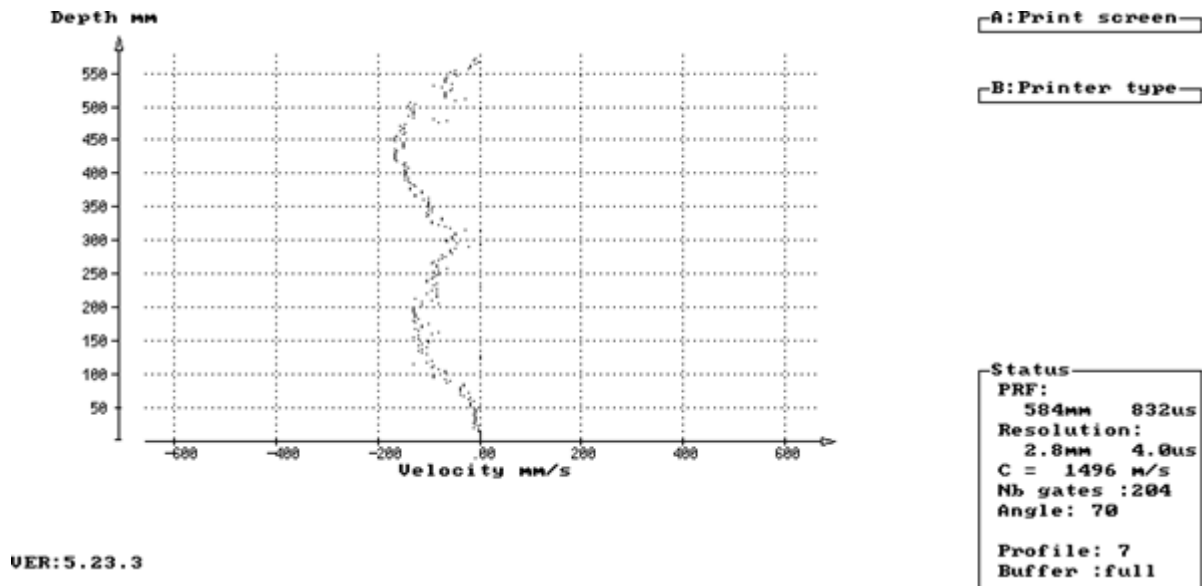


Figure 2 – Sample velocity profile generated by ultrasonic Doppler system

The Acoustic Doppler Velocimeter (ADV) system was positioned at 10 rotor diameters downstream of the turbine blade position, in order to record the variation in instantaneous velocity at the height of the blade hub. A sampling frequency of 25Hz was used with a total recording period of 90 seconds per experiment, giving around 2250 data points.

General flow conditions in the flume were measured using a magnetic flow meter and ultrasonic depth gauges. The height of water flow was measured using ultrasonic depth positioned at 3.8m, 18.5m (1.65m behind the installation position) and 38.5m downstream from the inlet of the flume. The magnetic flow meter was used to measure the bulk flow rate through the flume, and was installed on the recirculation system. An image illustrating the relative positions of the centrally-located flow measurement equipment is shown in Figure 3.

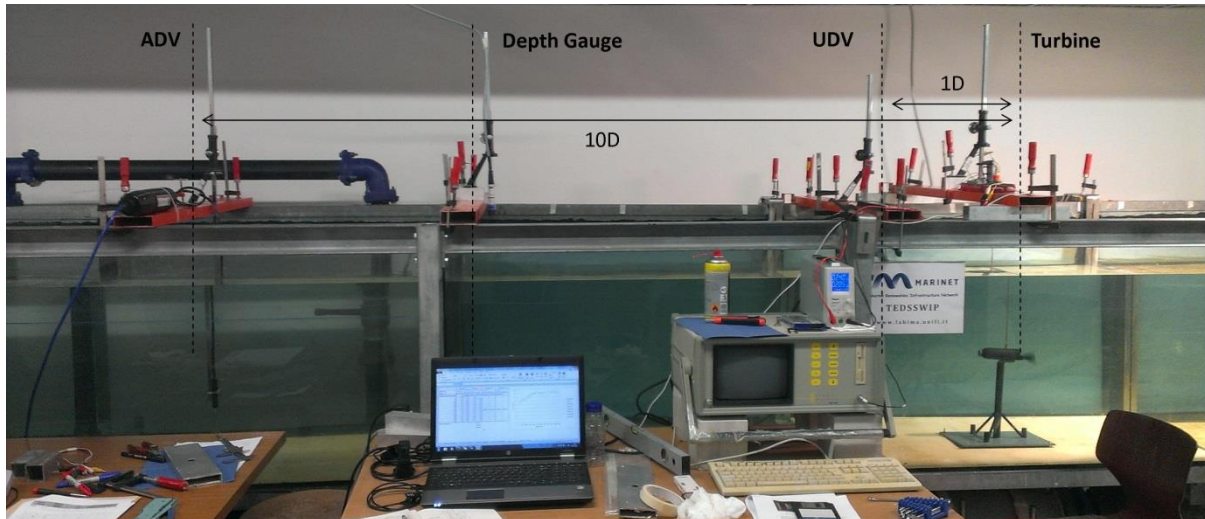


Figure 3 – Centrally-located flow measurement equipment and turbine in situ

2.3 FLOW CASES

2.3.1 $C_p - \lambda$ plots

The primary aim of the experimental work was to measure power coefficient (C_p) vs. tip speed ratio (λ) for the turbine mounted on each of the three support structure designs.

C_p is a measure of the power extracted by the turbine relative to the theoretical maximum power available in the water. Maximum power (P) is calculated based on the swept area (A), velocity (U), and density of the fluid (ρ), as described below:

$$P = \frac{1}{2} \rho A U^3$$

λ describes the ratio of the tangential rotational speed of a turbine device (rotational speed ω , blade radius R) to the flow speed in which it operates. The ratio is given as follows:

$$\lambda = \frac{\omega R}{U}$$

Experiments were conducted at λ values of 2, 3, 4, 5, and 6 and used to plot a $C_p - \lambda$ curve, Each experiment comprised two separate tests, conducted with and without the blades in place, to allow the calculation of blade torque as described in Section 3.3.1. Additional data was also collected for each support structure case in the form of velocity profiles at 10D downstream. These were recorded using the ADV equipment and processed using MATLAB to produce centreline streamwise velocity plots for every test, and for additional cases without support structures in the flume.

2.3.2 Experimental cases

In all cases, the flume was operated at a flow rate of around 73l/s, with the precise flow in each case being measured by the magnetic flow meter. The maximum recorded variation from a flow rate of 73l/s was 1.4%. A depth of 600mm was used in all cases, again measured precisely in each case using the three ultrasonic depth gauges described previously. The flume width of 800mm yields a cross-sectional area of 0.48m². With a flow rate of 73l/s, this yields an approximate bulk flow velocity of 0.152m/s through the flume.

Experiments were conducted at $\lambda = 2, 3, 4, 5,$ and 6. Turbine rotational speed was set using the motor and encoder system in order to produce the appropriate value of λ . This required rotational speeds ranging from $\omega = 2.5\text{rad/s}$ to $\omega = 8.6\text{rad/s}$, equating to approximately 23.5 and 82 revolutions per minute, respectively. These experiments were conducted with and without blades in each case, for each of the four support structures, giving a total of 40 tests.

Additional tests were also conducted to measure flow conditions of the empty flume, and to generate velocity profiles. Velocity profiles were also recorded in each experimental case (5 values of λ , with and without blades, for three support structures). These tests comprised ADV velocity measurements at the horizontal centre point of the flume, at twelve vertical positions from the flume base, at a spacing of 50mm (ie. 0mm, 50mm, 100mm, 150mm, 200mm, 250mm, 300mm, 350mm, 400mm, 450mm, 500mm, 550mm above the flume base). Due to the requirement of the ADV unit head to remain submerged, it was not possible to record the velocity profile over the top 50mm of the water flow. An ADV sample rate of 25Hz and sample time of 90 seconds was used in all cases.

2.4 CALCULATION

2.4.1 Blade Torque

In order to calculate the torque generated by the turbine blades, it was necessary to undertake a calculation to isolate the power generated by the blades. As has been discussed previously, the turbine blades were driven using an electric motor, in order to control the speed of the blade rotation and thus value of λ . This was achieved through the monitoring of the rotational speed of the blades ω , as recorded by the encoder and displayed live during the operation of the turbine. In order to calculate the blade generated torque, each experiment was conducted twice: Initially with blades in place (power applied P_{appB}), and subsequently with the turbine blades removed (P_{appNB}). In both cases, the same value of ω was used, but the required power to drive the turbine at this speed was different, due to the reduction in power requirement caused by the rotational force generated by the blades. In order to calculate the blade generated power, the difference between the with and without blade cases is analysed to yield the power contribution from the blades themselves.

$$P_B = P_{appNB} - P_{appB}$$

2.5 DATA PROCESSING

2.5.1 ADV data processing

The quality of ADV recording can be monitored using signal-to-noise ratio (SNR) and correlation. An SNR value is the ratio of the amplitude of coherent signal responses to that of background noise responses. A mean value of greater than 15dB is recommended by manufacturers, and is likely to yield results with an uncertainty of around 1%. Mean SNR values for the current study were around 18dB in all experimental cases.

Correlation values indicate the similarity of two subsequent signals as a percentage. In this case, mean values of 80% and above are recommended for reliable results. Correlation was used as a post-processing filter for ADV data. A MatLab script was written to exclude velocity data which corresponded to a correlation lower than a set threshold value. This value was set at 80% for all analysis. Filtering using the 80% threshold resulted in the removal of approximately two-thirds of the recorded data in each case.

2.5.2 UDV data processing

Due to the nature of the design of the equipment, the accuracy of the UDV measurement reduces with reducing distance to the unit head, meaning that values recorded towards the top of the flume depth may be less accurate than those recorded at lower depths [5]. It is estimated that results may suffer from errors within a region of around 100-150mm depth below the unit head, corresponding to water depths of 450mm in the flume arrangement described herein. In order to avoid any such issues, UDV profiles have been extracted from the recorded data only up to the top of the turbine swept area, at a height of 393.5mm above the flume base. UDV data was imported using a MatLab script originally written by Hannu Karema.

2.5.3 Turbine encoder data processing

Data from the turbine speed encoder and current measurement unit were both recorded via a LabJack U12 data acquisition system. The output from the encoder was recorded as a square wave output, with a high voltage recorded as an encoder disc hole passed the sensor, and a low output recorded between holes. From this data a

simple program was used to generate time series turbine velocity data. The current measurement module generated data as a voltage variation from its constant input voltage, with a variation of 185mV indicating a current of 1A. Again, a simple program was used to translate this voltage into the actual measured current supplied to the motor over time.

2.6 TESTS

2.6.1 Test Plan

An outline of the work and tests undertaken on each day of the access period is detailed in the table below.

	Preparatory work	Testing
Day1	Model assembly	
Day 2	Model assembly	
Day 3	Turbine unit & instrumentation installation	
Day 4	Turbine unit testing	
Day 5	Turbine unit testing & profile generation	
Day 6		Design 1 ($\lambda = 2$)
Day 7		Design 1 ($\lambda = 3-6$)
Day 8		Design 2 ($\lambda = 2-6$)
Day 9		Design 3 ($\lambda = 2-6$)
Day 10	Data collation & checking	Design 4 ($\lambda = 2-6$)

Table 1 - Tests as carried out during the access period

2.7 RESULTS

Analysis of results is currently ongoing and further data will be published in due course. Initial $C_p - \lambda$ data highlights the variation in flow conditions at which optimal performance is achieved, as illustrated in Figure 4.

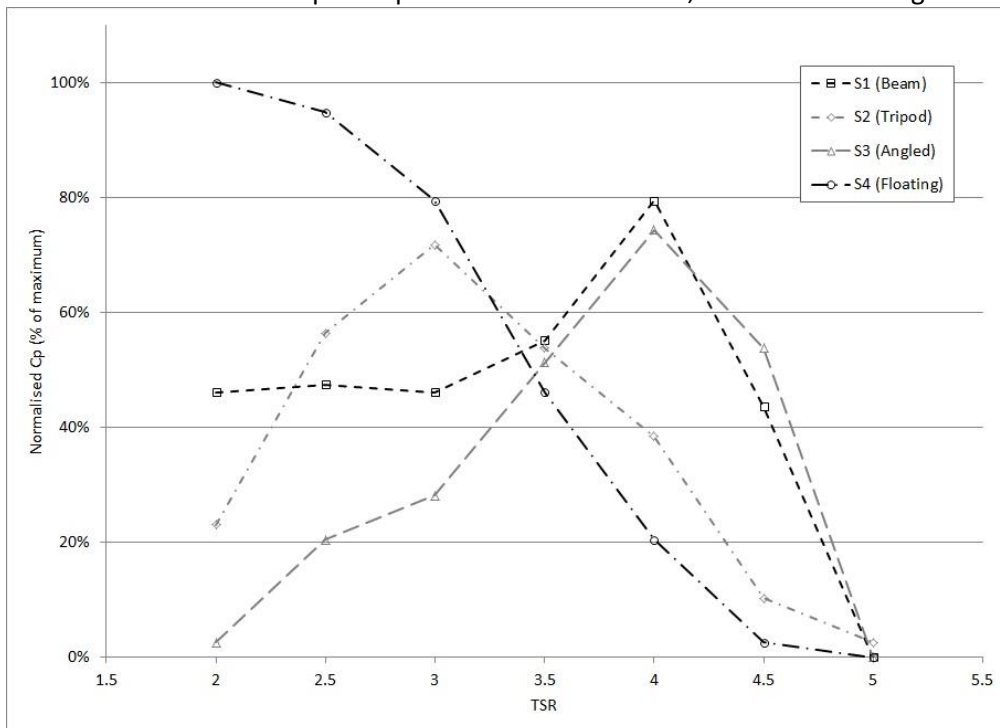


Figure 4 - $C_p - \lambda$ plots for four support structure designs as tested during TEDSSWIP project

2.8 ANALYSIS & CONCLUSIONS

The four designs of support structure tested yield their optimal performance value at a range of values of λ from 2 to 4. This highlights the importance of the selection of support structure design for the prevailing flow conditions. Though further work is required to fully understand the precise reasons for these differences, a correlation in the measured data exists between turbine performance and turbulence intensity in the near downstream region, with a high turbulence intensity leading to a reduction in the power generated by the turbine. It is possible that turbulence and flow structures generated by the support structure have a significant effect on the blades, and thus the power generating potential and energy yield of a turbine.

3 MAIN LEARNING OUTCOMES

3.1 PROGRESS MADE

3.1.1 Progress Made: For This User-Group or Technology

The aims of this project have been achieved, and a large volume of data on the performance of a model tidal stream turbine installed on four support structure designs has been produced. This data has been initially analysed and results illustrate that there are significant differences in performance between the four support structure installations.

3.1.1.1 Next Steps for Research or Staged Development Plan – Exit/Change & Retest/Proceed?

The next stage of this work requires the continued analysis of this data in order to fully understand the effects which lead to the observed differences in performance between the four device support structure designs. Once this stage is complete, the data will be used as part of a further EPSRC-funded project to generate computational models of the support structures tested, and to replicate their experimentally-measured performance using a computational model. Following this, further designs of support structure will be studied using the validated computational model, eventually resulting in the proposal of optimised designs of device support structure. It is hoped that these optimised designs can then be tested experimentally at the UNIFI-CRIACIV Wave-Current Flume.

3.1.2 Progress Made: For Marine Renewable Energy Industry

The use of a driven turbine setup in order to measure blade torque appeared to work effectively, and is a more controllable system than the alternative “free turbine” method. The driven turbine method has been used by other groups conducting similar research, and is described in detail in the journal article referred to in Section 4.1. Further progress is anticipated to be made as result analysis continues, particularly into the understanding of turbulent flows around tidal turbine support structures, and their interaction with blade turbulence.

3.2 KEY LESSONS LEARNED

- Experimental models constructed for flume testing should be as large as is feasible, since small parts were found to cause installation challenges
- Experimental models constructed for flume testing should be “over engineered” where possible, for example using metal construction in place of plastic parts
- Instrumentation and measurement equipment should be tested for compatibility prior to arrival at the experimental facility
- For the scale model testing of tidal stream turbines, the use of motor-driven models allows control of rotational speed, and may be a more reliable technique than the “free turbine” technique
- The time required for experimental setup and preparation of tests may take longer than anticipated (particularly on the first visit to a facility) and should not be underestimated.

4 FURTHER INFORMATION

4.1 SCIENTIFIC PUBLICATIONS

List of any scientific publications made (already or planned) as a result of this work:

- Walker, S., Cappiotti, L., Howell, R. *MARINET "TEDSSWIP" project: The effect of a tidal turbine support structure on device performance*. IJOME. In review (submitted 10/10/14)

4.2 WEBSITE & SOCIAL MEDIA

UoS websites: www.sheffield.ac.uk/mecheng & www.tidalsheffield.wordpress.com

UNIFI website: <http://www.labima.unifi.it/CMpro-v-p-18.html>

YouTube Link(s): www.youtube.com/user/shefunimecheng

LinkedIn/Twitter/Facebook Links:

www.facebook.com/SheffMechEng

https://www.linkedin.com/groups?home=&gid=4625823&trk=anet_ug_hm

@sheffmecheng

@mrstuartwalker

5 REFERENCES

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