User Project Structural and Performance Effects of Current and Waves on Tidal Turbine

Project Acronym SPECuWaTT

Project Reference Number 1590

Infrastructure Accessed CRIACIV_LABIMA - Wave Current Flume

Infrastructure
Access
Reports

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MaRINET2

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

European Commission

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1 Introduction & Background

1.1 Introduction

Oceans are hostile environments for engineered structures. Though similar to oil and gas and offshore wind structures, tidal turbines have unique characteristics, and the effect of a lifetime in this environment is currently not well understood. Such an understanding is crucial to the efficient and cost-effective design of tidal turbines.

Furthermore, the effect of waves on the performance of a tidal turbine is not sufficiently well understood. Environments in which tidal turbines are likely to be installed are often subject to highly energetic waves, which impact the performance of the turbine by altering the flow profile reaching the turbine blades, and also impact the structural loading on the turbine support structure.

This study thus aimed to test a scale model of a tidal turbine under the effect of realistic combinations of flow and wave cases and to record the impact on turbine performance and structural deflection of the support structure.

Two real sites were used to generate the input data for this study, one in the Messina Strait in the Mediterranean Sea, and on in the Sound of Islay in the North Atlantic. Hindcast and recorded wave and tidal flow data for these cases was used to establish scale wave and tidal flow cases for each site, under which a 1:81 scale turbine was tested in the LABIMA flume.

1.2 Development So Far

1.2.1 Stage Gate Progress

Previously completed: ✓

Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Case creation	
• Identify suitable tidal turbine installation sites	✓
• Collect wave and tidal flow data for sites	✓
• Categorise data to give benign, moderate and extreme hourly conditions	✓
• Scale wave and tidal flow data for flume use	✓
• Confirm flume ability to generate required cases	✓
Stage 2 – Model design and construction	
• Select turbine scale based on LABIMA flume size	✓
• Produce CAD model of turbine blades and manufacture by SLS	✓
• Install strain gauge array and generator to record deflection and turbine performance	➲
Stage 3 – Experimental Testing	
• Investigate structural deflection and turbine performance under a range of wave and tidal flow conditions, to include: • Upstream-facing blades • Downstream-facing blades • Waves with tidal flow • Waves against tidal flow	➲
Stage 4 – Long-term performance model creation	
• Construct statistical "year of data" cases by concatenation of cases created in stage 1	
• Apply results of experimental performance testing to each hourly case during year of data	

STAGE GATE CRITERIA	Status
• Generate annual performance model for a turbine at a range of location sites and site conditions	
• Generate annual turbine performance forecasts for benign, moderate and extreme years	
Stage 5 – Long-term structural model creation	
• Generate Finite Element (FE) model of tidal turbine and support structure from existing CAD	
• Apply scaled structural deflection results for cases studied in Stage 3 to FE model	
• Concatenate benign, moderate and extreme cases created in Stage 1 to give annual structural deflection regimes.	
• Run FE model over generated annual deflection regimes to give total structural effects of annual cases generated in Stage 1	
• Use FE model subsequently to study performance vs structural effects for a range of climate scenarios and tidal turbine installation locations	

1.2.2 Plan for this Access

The focus of this access is to test a scale model of a tidal turbine under a range of conditions based on those recorded at real sites with the potential for tidal turbine installation. The scale model to be tested is shown in Figure 1.1.

Figure 1.1 Scale model tidal turbine as tested

Prior to testing, characterisation and sensor calibration will be undertaken to ensure the validity of results.

1.2.3 Characterisation and Validation

Turbulence is critical in water channel tests. Water flume turbulence characteristics must match those of real tidal installation cases, in order to ensure accurate replication of reality. To ensure this, turbulence intensity will be recorded at the turbine installation position, and turbulence-generating structures will be installed if necessary.

Prior to testing, the water flume will be characterised by recording profiles at the turbine installation position for each of the flow and wave cases to be subsequently tested. Strain gauges will also be calibrated against a load cell in order to ensure the force applied to the turbine is correctly measured.

1.2.4 Turbine testing

Prior to arrival at the test facility, sites will be selected and flow and wave data gathered. Hindcast and recorded data will be used to generate hourly data, classified as benign, moderate, or extreme (B, M, or E respectively) in terms of wave height, wave period, and tidal velocity.

Scaling to the flume size and combining these classifications gives a series of scaled condition scenarios, under which the scaled turbine model will be tested. Two major aspects will be recorded: Turbine performance and turbine structural deflection. Performance will be recorded by recording the output of the turbine generator, and structural deflection will be recorded using strain gauges mounted on the support structure. The instrumented turbine model is shown in the figure below (maybe in work carried out section instead?)

2 Outline of Work Carried Out

2.1 Setup

The experimental testing part of the SPECuWaTT project, as described in Section 1.2.1., was undertaken at the LABIMA Wave-current flume during October and December 2018. A CAD schematic of the LABIMA Wave-current flume is shown in Figure 2.1.

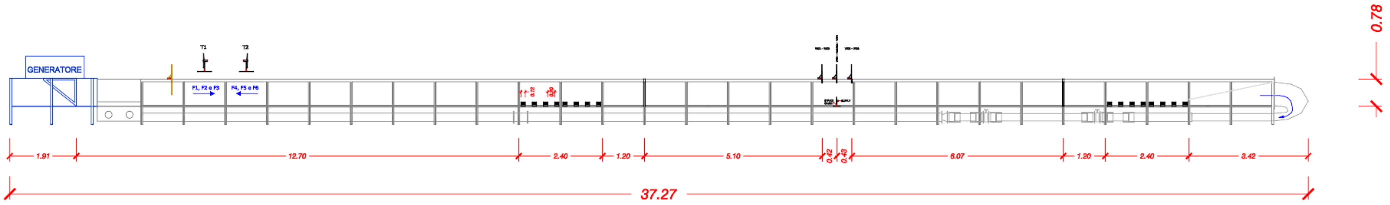


Figure 2.1 LABIMA Wave-current channel CAD diagram

The 1:81 scale turbine model was installed 21.83m from the wave maker (shown to the left of Figure 2.1), and 12.6m from the channel end.

An absorbing structure was added to the channel to diffuse wave power and reduce reflection from the end of the channel. This perforated steel structure was 2.4m in length and reached across the channel, angled upwards from the base to above the height of the highest waves to be tested. The absorbing structure used is shown in Figure 2.2 (right).

2.1.1 Characterisation & Calibration

Prior to testing, the channel was characterised in order to capture flow profiles and turbulence data for the cases to be tested. Profiles were captured using a Nortek Vectrino Acoustic Doppler Velocimeter at the turbine installation location for each of the wave and flow cases subsequently used to test the turbine. During characterisation it was noted that the turbulence intensity of the empty channel was much lower than that expected of a real tidal installation site, and (in common with many other experimental studies) turbulence-generating structures would be used.

The location of the wave-making equipment is fixed, so in order to facilitate the eventual testing of cases with wave propagation and tidal flow in the same direction, and cases with wave propagation opposing tidal flow, it was necessary to simulate tidal flow from both ends of the channel. Consequently, turbulence-generating structures were installed both upstream and downstream of the turbine. A combination of blocks and mesh were used. Cubic stone blocks of 120mm width were installed with a cross-channel separation distance of 150mm and a streamwise separation distance of 200mm between rows. Alternating rows of two and three blocks were used, covering a total distance of 2.4m between 6.6m and 9.0m downstream of the turbine installation location. A stainless steel mesh of 12mm grid size was installed across the channel and over its full depth, at a distance of 5.4mm downstream of the turbine installation location. The turbulence-generating blocks are illustrated in Figure 2.2 (left).

Figure 2.2 Turbulence-generating blocks (l) and wave absorbing structure (r)

2.2 Turbine Model

The 1:81 scale turbine model used in this study was a three-blade horizontal axis turbine, as are most commercial tidal turbine concepts. The blade profile was based on that of a commercial design and was manufactured in polyacrylate at the University of Sheffield Department of Applied Inkjet Printing. The turbine blades were each 100mm from root to tip, with a 12° degree root-tip twist, a tip chord of 8mm and a root chord of 26mm. The blades were mounted on a nacelle, which was itself fixed to the turbine generator. No gearbox or other power transfer mechanisms were used. The support structure of the turbine was a simple 8mm diameter post design without a complex support base, tripod or other fixing arrangement. This design was chosen to allow the measurement of structural deflection on a homogeneous support structure. The turbine and support structure were mounted on a steel base of 200mm x 200mm and 7mm thickness, designed to hold the turbine in position without a requirement to fix it to the base of the channel. The support structure was 117mm in length from the base to the generator, meaning that the centre of the nacelle was 137mm above the channel base.

In order to measure performance and structural deflection, the turbine model was equipped with a generator and strain gauges. A small DC motor (model MFA RE-385) was used as a generator. The voltage produced by the generator was measured using the LABIMA Data Acquisition system. Since the key performance output of the turbine in this study is the relative power generation, generator output was not scaled or calibrated to rotational speed. Instead, generator voltage was used to give a direct comparison between cases.

We installed copper foil strain gauges (model BF350, 350Ω with sensitivity coefficient 2.1) on the turbine support structure at a height of 58.5mm above the base of the support structure. One gauge was installed on the upstream-facing portion of the support structure, and another perpendicular to this on the side of the support structure. Gauges were installed in a half-bridge configuration, and were supplied with 5V via the LABIMA data acquisition system and deflection recorded using the same system.

In order to correlate support structure deflection and strain gauge voltage output, the gauges were calibrated using a load cell. A rigid steel bar was fixed between the load cell and the centre of the nacelle, and the turbine was incrementally moved towards the load cell whilst recording both strain gauge and load cell outputs. Testing was repeated multiple times and were found to be unaffected by the direction of movement of the structure (i.e. whether the turbine was moving towards or away from the load cell). A linear relationship was found between the deflection of the structure and the load applied, as illustrated in Figure 2.3.

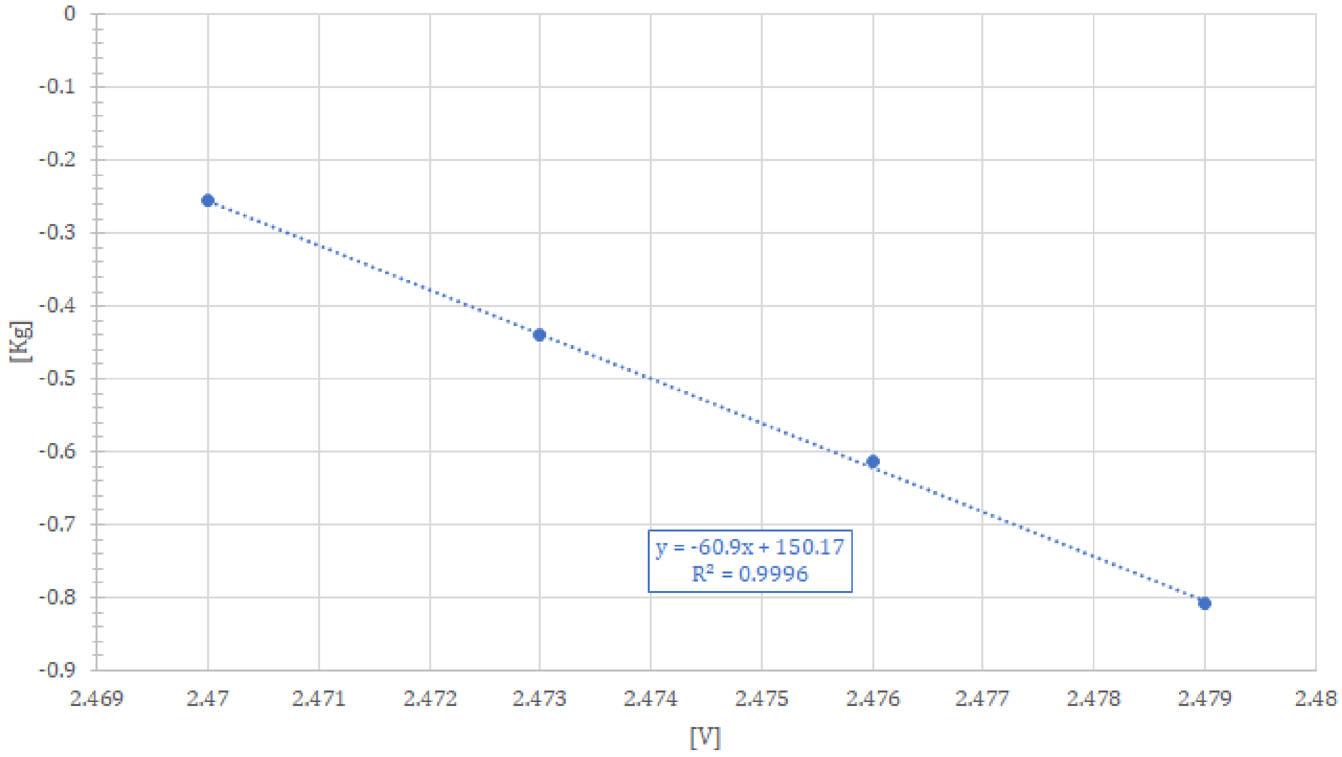


Figure 2.3 Strain gauge / load cell calibration

2.3 Test Plan

As discussed previously, experimental cases were developed and at this stage were scaled for replication in the LABIMA channel. The specific cases tested, in real and scale versions, are given in Table 2.1.

Case	Location / Level	Flow rate	Name	Wave height / period	Name
1	Messina Strait: Benign	Real: 0.8m/s Scale: 0.1m/s	F1 / F4	Real Height: 2.4m Real Period: 7.2s Scale Height: 0.03m Scale Period:0.8s	H1
2	Messina Strait: Moderate Sound of Islay: Benign	Real: 1.3m/s Scale: 0.16m/s	F2 / F5	Real Height: 4.0m Real Period: 7.2, 9.0, 10.8s Scale Height:0.05m Scale Period:0.8, 1.0, 1.2s	H2 (1.0s) H4 (0.8s) H5 (1.2s)
3	Messina Strait: Extreme Sound of Islay: Moderate	Real: 1.7m/s Scale: 0.21m/s	F3 / F6	Real Height: 5.7m Real Period: 7.2, 9.0, 10.8s Scale Height: 0.07m Scale Period: 0.8, 1.0, 1.2s	H3 (1.2s) H9 (0.8s) H10 (1.0s)
4	Sound of Islay: Extreme	Real: 2.1m/s Scale: 0.26m/s	F7 / F8	Real Height: 8.9m Real Period: 15.3s Scale Height: 0.11m Scale Period: 1.7s	H8

Table 2.1 Flow and Wave cases as tested

These cases were subsequently combined to give a matrix of test cases. For each flow case, tests were carried out in a no wave case, and over a range of wave cases. This was also repeated for two direction cases, one where the flow and wave propagation directions were the same, and one where the flow and wave propagation directions were opposing. Tests were carried out with the turbine facing upstream (i.e. flow into the turbine blades) and the turbine facing downstream (i.e. flow into the rear of the turbine nacelle). A total of 14 tests without a turbine and 65 with a turbine were carried out.

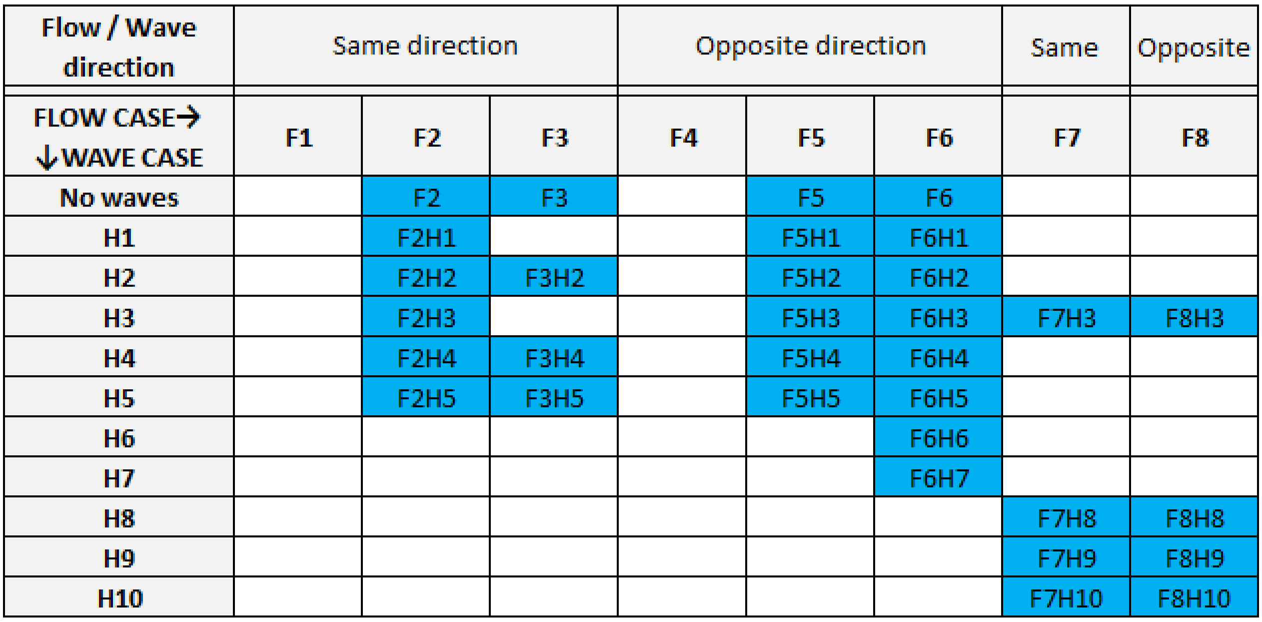
During initial tests with flow case 1 (F1) it was found that insufficient power was provided to turn the turbine, so this flow case was not used. The F4 case, which has the same flow rate as the F1 case but an opposite wave direction, was therefore also removed. However, the Messina Strait benign wave case (H1) was still tested combined with moderate and extreme flow cases. After the successful completion of all the planned tests, further tests were added to allow the study of the effect of irregular waves. The full matrix of tests carried out and the naming convention used is shown below.

FLOW CASE→ ↓WAVE CASE	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
No waves	F1	F2	F3	F4	F5	F6	F7	F8
H1	F1H1			F4H1				
H2		F2H2			F5H2			
H3								
H4								
H5								
H8							F7H8	
H9							F7H9	
H10								

Table 2.2 Flow and Wave cases: No turbine

Flow / Wave direction	Same direction			Opposite direction			Same	Opposite
FLOW CASE→ ↓WAVE CASE	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
No waves	F1	F2	F3		F5	F6	F7	F8
H1		F2H1	F3H1		F5H1			
H2		F2H2	F3H2		F5H2	F6H2		
H3		F2H3	F3H3		F5H3		F7H3	F8H3
H4		F2H4	F3H4		F5H4	F6H4		
H5		F2H5	F3H5		F5H5	F6H5		
H8							F7H8	F8H8
H9							F7H9	F8H9
H10							F7H10	F8H10

Table 2.3 Flow and Wave cases: Turbine facing upstream



Flow / Wave direction	Same direction			Opposite direction			Same	Opposite
FLOW CASE→ ↓WAVE CASE	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
No waves		F2	F3		F5	F6		
H1		F2H1			F5H1	F6H1		
H2		F2H2	F3H2		F5H2	F6H2		
H3		F2H3			F5H3	F6H3	F7H3	F8H3
H4		F2H4	F3H4		F5H4	F6H4		
H5		F2H5	F3H5		F5H5	F6H5		
H6						F6H6		
H7						F6H7		
H8							F7H8	F8H8
H9							F7H9	F8H9
H10							F7H10	F8H10

Table 2.4 Flow and wave cases: Turbine facing downstream

Each test with waves took the following form: First, a 10 second period without waves, then a 30 second period of wave generation, followed by a 30 second period without wave generation

2.4 Results

2.4.1 Channel turbulence

Prior to testing with waves, turbulence intensity was recorded as described in the previous section. Two examples of streamwise turbulent intensity profiles are shown in the figure below. The two examples given are at the two extremes of the flow rate cases tested: F1 and F7 respectively. F1 corresponds to a volume flow rate of 25l/s through the channel, giving a mean velocity of 0.1m/s. F7 corresponds to a flow rate of 62.5l/s, giving a mean velocity of 0.26m/s. As shown below and as would be expected, the high velocity case exhibits a much greater turbulent intensity with a maximum value of over 25%. The low velocity case exhibits streamwise turbulent intensity of less than 5%.

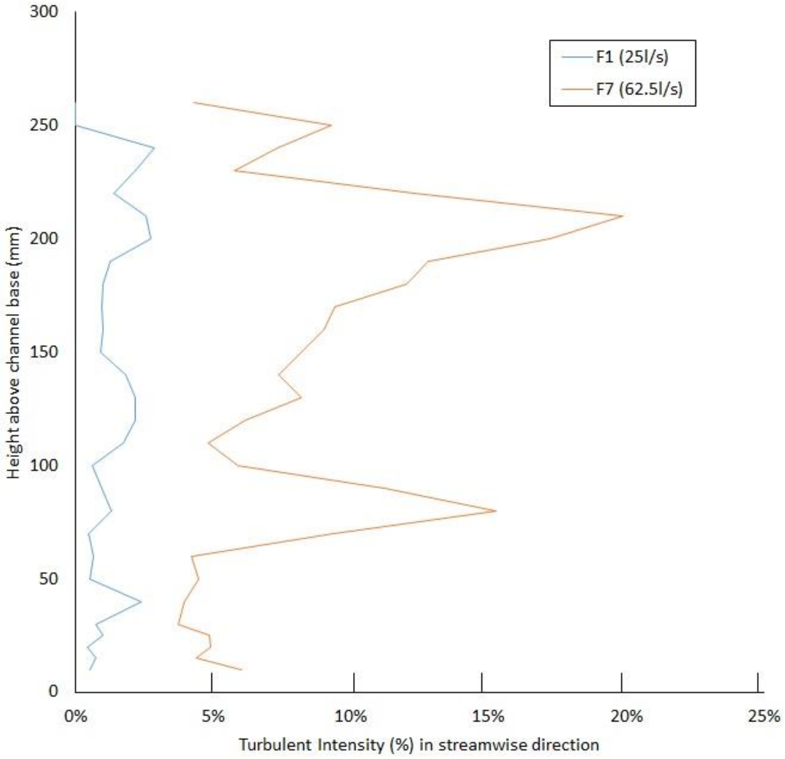


Figure 2.4 Sample turbulence intensity plots for F1 and F7 cases

Turbulent intensity data is an important baseline for performance tests, and will be used in further study in combination with power and support structure strain results.

2.4.2 Wave results

Initial data from each test, as shown in Figure 2.5, has been collated. The test format described in section 2.3 can be seen in the wave-generator paddle displacement shown below (the lower, dark blue line in each case represents the displacement of the wave generator). In some cases with flow in the opposite direction to wave propagation and high flow rates it was found that the 30 second period was insufficient to allow the waves to reach the turbine. In these cases, the wave generation time period was extended to 60 seconds. The upper image below shows the case where wave propagation and flow were opposing, and it can be seen that the waves take marginally longer to reach the turbine than in the lower case (where the waves and flow are in the same direction). In greater flow rate cases this effect was exacerbated.

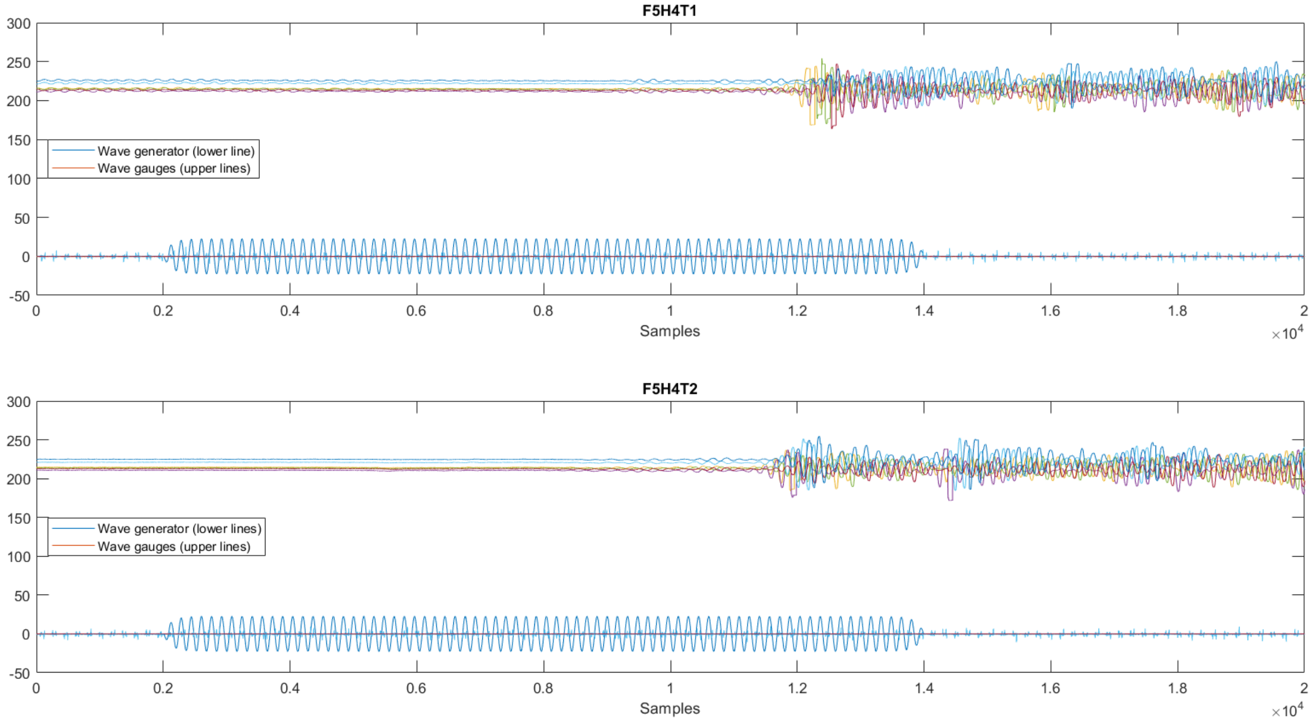


Figure 2.5 Sample data from experiments with flow in the same (lower) and opposing (upper) direction to wave propagation

2.4.3 Power and support structure strain results

Turbine power output was monitored by measuring generator voltage throughout each test. Following completion of testing this subsequently allowed a comparison between cases to determine the overall effect of wave and flow cases on the turbine power generation, both over the course of a test and at specific temporal positions during the wave action, for example.

In order to assess the impact of waves on performance, results were analysed for the same flow rate with a range of wave conditions. Examples of this data are shown in Figure 2.6 and Figure 2.7, for the F2 and F3 flow cases.

Similarly, results were studied in terms of structural deflection, for a range of wave conditions under the same flow case. These results are shown in Figure 2.8.

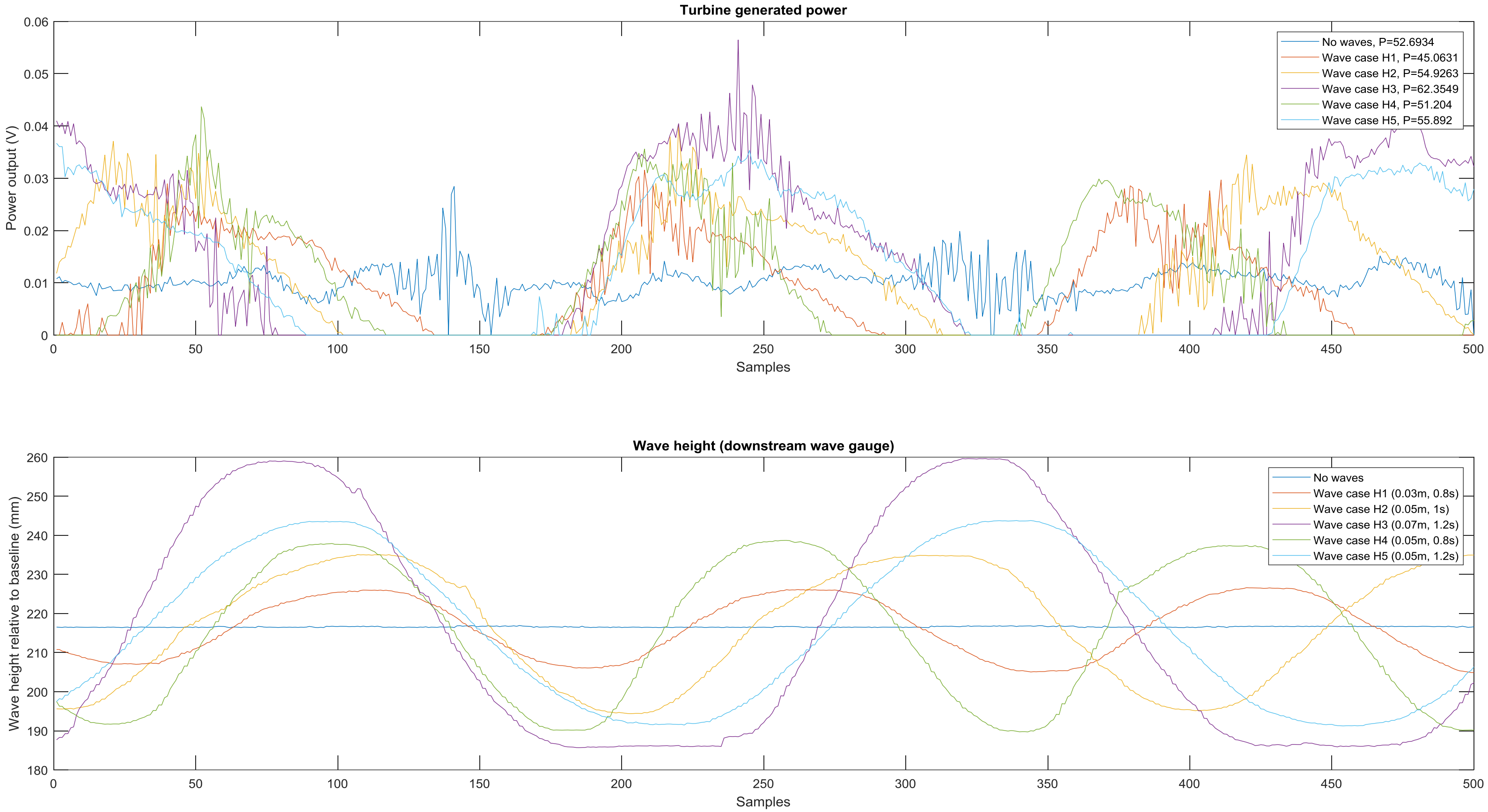


Figure 2.6 Turbine-generated power for sample F2 flow case with no waves and wave cases H1, H2, H3, H4, H5 over 2.5 seconds

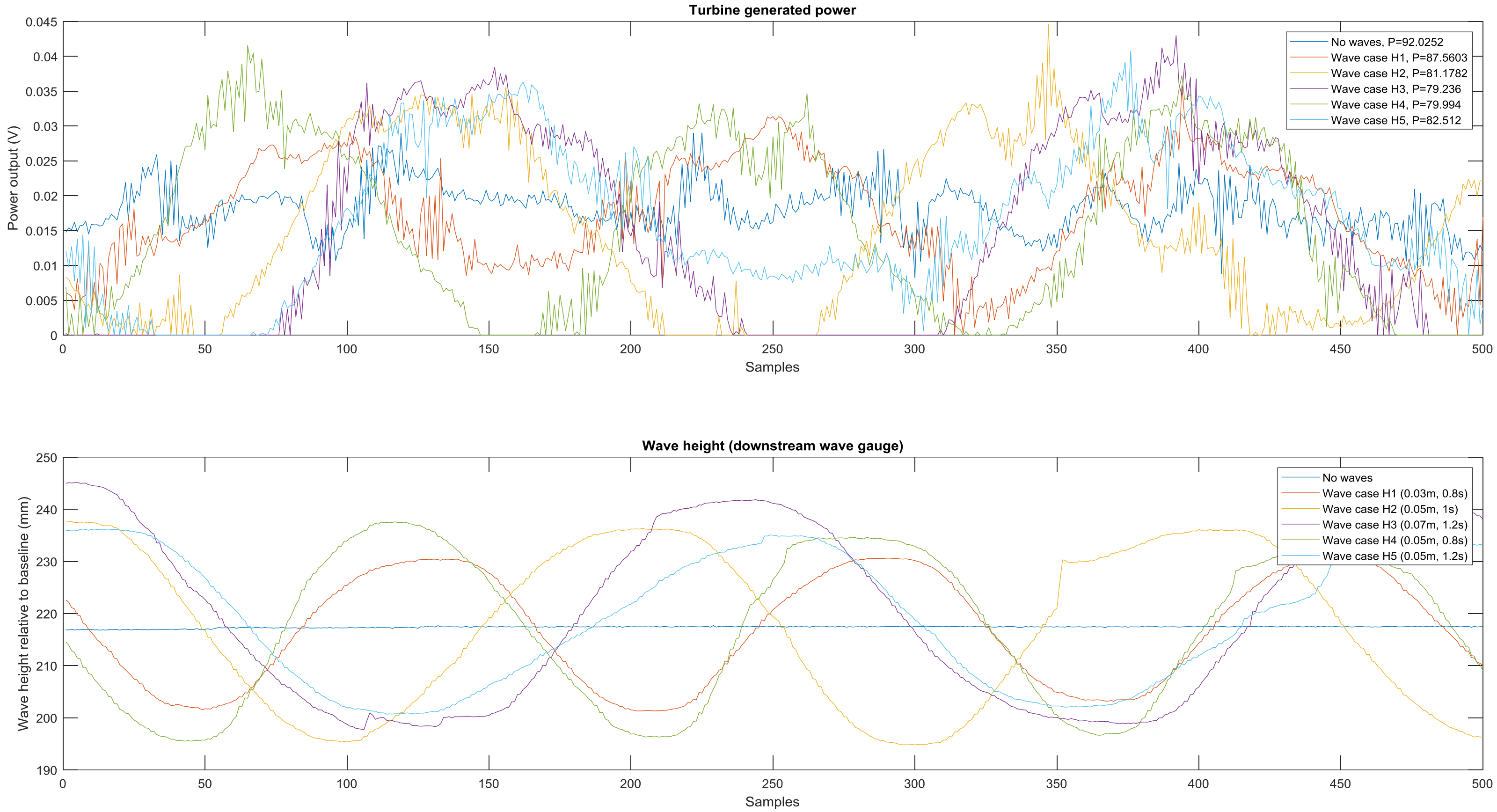


Figure 2.7 Turbine-generated power for sample F3 flow case with no waves and wave cases H1, H2, H3, H4, H5 over 2.5 seconds

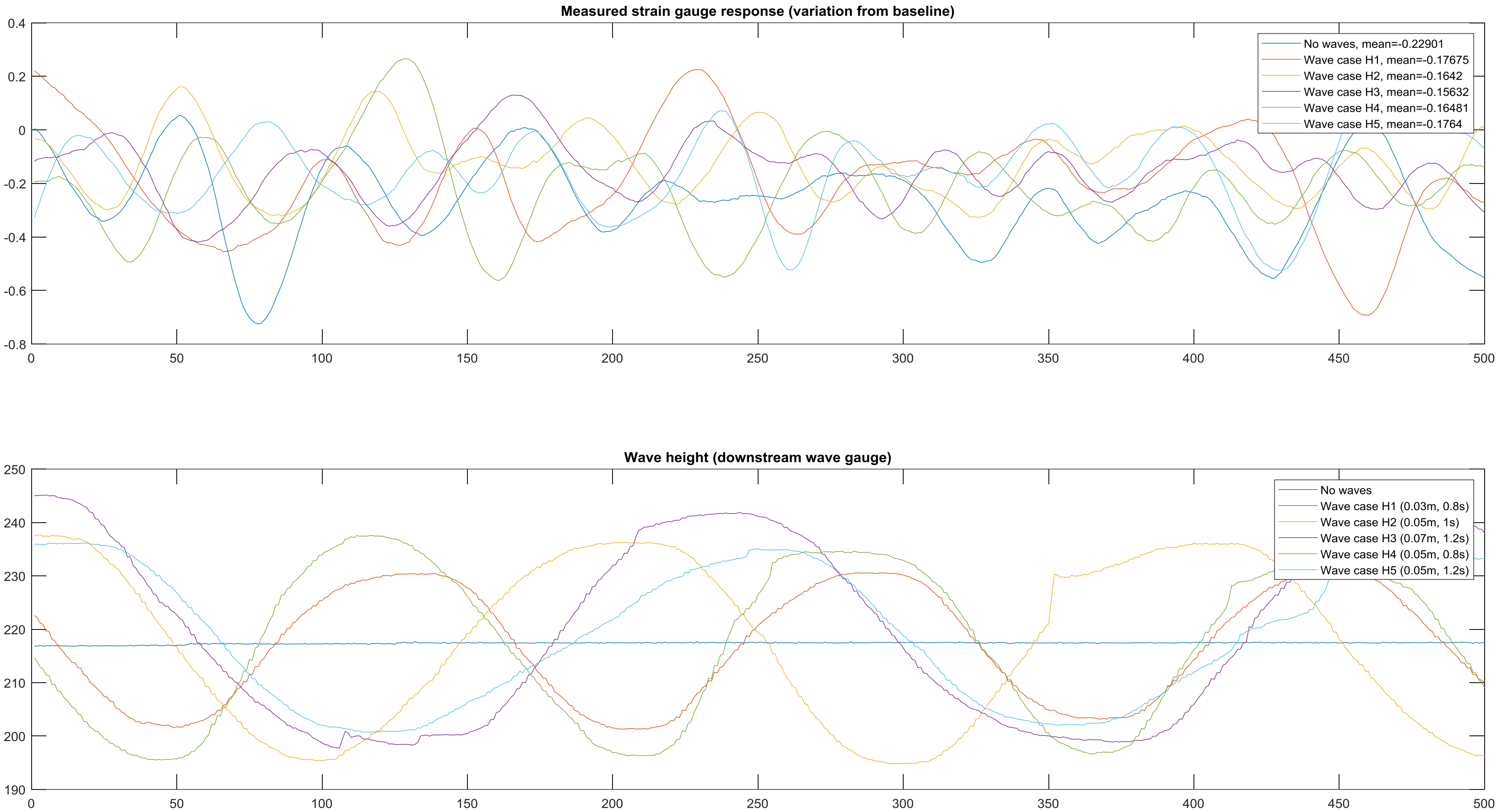


Figure 2.8 Turbine support structure strain for sample F3 flow case with no waves and wave cases H1, H2, H3, H4, H5 over 2.5 seconds

The power generation data above illustrates one of the key initial findings from these results: The power generated by the turbine is linked, as expected, to the flow rate, with increasing flow rate yielding increasing power output in the no wave cases. However, the introduction of waves has a varying impact on power output in different flow rate cases. In the lowest flow rate case tested (F2), the maximum total power generation was produced not in the no wave case, but in the case with the largest wave amplitude. In cases with increased flow rate, maximum power generation was produced in the no wave case, with power gradually reducing with increased wave height.

2.5 Database

The data resulting from the SPECuWaTT project has been stored in the LABIMA online archive. All recorded variables including wave gauge data, wave maker position, turbine strain gauge and generator output are included in the inline database, which is accessible at the following location:

http://people.dicea.unifi.it/cappietti/Research/MARINET2/SPECuWaTT/DataBase

Cases are titled using the FxxHxxTxx convention, where T1 describes the turbine facing upstream and T2 the turbine facing downstream. Flow and wave cases are as described in Table 2.2, Table 2.3, and Table 2.4.

2.6 Analysis & Conclusions

Analysis of the data collected is ongoing, and it is intended that a journal publication and conference presentation will result from further analysis. An abstract for a presentation of these results at the EWTEC 2019 conference has been accepted. Two initial conclusions of interest are detailed below:

- For most flow cases, maximum total power is generated in the no wave case. However, in lower flow rate cases the difference between power generated in wave and no wave cases appears to be smaller, and in the lowest flow rate case the maximum power is actually generated in the largest wave case.
- Support structure strain appears to be greatest in the cases with short wave period cases, and appears to be impacted more by the wave period than the absolute amplitude of the waves.

3 Main Learning Outcomes

3.1 Progress Made

The plan for this access, detailed above, states:

"*The focus of this access is to test a scale model of a tidal turbine under a range of conditions based on those recorded at real sites with the potential for tidal turbine installation*"

This has been achieved by testing a scale model tidal turbine over a total of 71 flow and wave cases based on the Messina Strait and the Sound of Islay installation sites. As has been stated, further data analysis is ongoing and results will be presented through conference and journal presentations, both their current stage and following further work to develop the long-term fatigue model discussed in previous sections.

3.1.1 Progress Made: For This User-Group or Technology

This user group is not a commercial enterprise, and the model tested is designed to be a generic representation of a tidal turbine, so the progress made for the user group is aimed to also be of use to the technology and industry as a whole.

The major progress made during this test is the expansion of the knowledge base on the impact of concurrent wave and current on a tidal turbine. This knowledge base has been added to with both turbine performance and structural deflection data.

3.1.2 Progress Made: For Marine Renewable Energy Industry

Ultimately, this work will be expanded to develop the lifetime fatigue model described in the introduction. It is envisaged that this model will be made available to others, and if other turbine designs were tested in the same way and with the same conditions, the fatigue model could be expanded into a comparative fatigue model. This subsequently could develop into an optimisation tool.

3.2 Key Lessons Learned

A small number of lessons learned have been identified at this stage. It is anticipated that more specific points will arise during data analysis.

- The size of a scale model turbine is key. The 1:81 scale used in this study results in a model of approximately 220mm blade diameter. This is suitable for testing, but it must be borne in mind that at smaller scales than this the instrumentation and monitoring of a turbine may become difficult (e.g. it may be difficult to find a suitable generator of small enough size)
- Ideally, the frictional characteristics of a turbine and generator system should be known prior to the design of experiments, to avoid issues such as the flow rate being insufficient to turn the turbine, as occurred in this case.
- In an experimental campaign of this type, the actual testing will take a relatively small amount of time. The bulk of time required will be for setup and characterisation testing.
- It is critical to monitor the test plan during the testing regime and if necessary to adapt the regime. In the case of this testing program, it was necessary to adapt the length of some tests to accommodate slow wave propagation.
- Motors used to drive water channel pumps can generate interference. It is important to consider this when designing experimental equipment, using shielded cabling for sensors and power measurements, for example, in order to reduce the effect of this on experimental results. Running a suitable number of characterisation and background tests is also useful to help correct the influence of issues of this type at a later stage.

4 Further Information

4.1 Scientific Publications

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

- Abstract "*A laboratory study on the effects of waves on the performance and structural deflection of a tidal stream turbine*" has been accepted for presentation at the EWTEC 2019 conference.
- A journal publication is planned. A journal such as Energies, Renewable Energy, or the Institute for Mechanical Engineers Part M (Engineering for the Maritime Environment) will be targeted.

4.2 Website & Social Media

Website:

- The project post access report, database and picture and video are available at: https://www.labima.unifi.it/vp-173-specuwatt.html

- Some updates have been published on a blog at https://tidalsheffield.wordpress.com

LinkedIn/Twitter/Facebook Links:

- Some updates have been published on Twitter at www.twitter.com/mrstuartwalker and www.twitter.com/LABIMA_UNIFI

Online Photographs Link:

- https://tidalsheffield.wordpress.com/2019/01/15/more-successful-work-at-labima/