Infrastructure Access Report

*Infrastructure*: CNR-INSEAN Circulating Water Channel

*User-Project*: SaPreC3T

Sabella Pre Commercial Tidal Turbine Testing

SABELLA SAS

Status: Final
Version: 01
Date: 08-Feb-2015
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](http://www.fp7-marinet.eu) for more details.

**Partners**

<table>
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<tr>
<th>Ireland</th>
<th>University College Cork, HMRC (UCC_HMRC)</th>
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### DOCUMENT INFORMATION

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### REVISION HISTORY

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<th>Date</th>
<th>Description</th>
<th>Prepared by (Name)</th>
<th>Approved By Infrastructure Manager</th>
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<td>08/02/2015</td>
<td>Writing of the document</td>
<td>Diane Dhomé</td>
<td>Fabio Di Felice</td>
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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.

LEGAL DISCLAIMER

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EXECUTIVE SUMMARY

SABELLA is a French company developing marine current turbines. CNR INSEAN is an Italian research institute specialised in hydrodynamics for propulsion and marine structures. It owes, among other facilities, a large pressurized circulating water channel, that SABELLA used for performing tests in the frame of MARINET. After first tests carried out within MARINET second call, SABELLA chose this facility again to perform new tests within MARINET fifth call. The purpose of these new tests was to study a rotor of a “Sabella D15” tidal turbine, which will be used in a pilot farm of around four turbines in the Fromveur Strait. The tests were made of two parts. First, performance tests were carried out. For this, the classical setup for marine propellers was adapted by INSEAN in order to test the turbine. The rotor was fully monitored which allowed obtaining forces, torque and efficiency. Several parameters were investigated: influence of an angle between the current direction and the rotor axis; influence of the free surface, importance of the blades on the total efforts, influence of the Reynolds number… The results were compared to the numerical studies in order to recalibrate the model and to have a reliable numerical model for future rotors designs. The second part of the tests consisted in near wake measurements by using Particle Image Velocimetry technique. The results are currently being investigated and will provide very useful input data for tidal turbines arrays patterns modelling.
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1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

SABELLA SAS is a company based in Quimper, France, that is developing a tidal turbine technology. Several tests have already been carried out. In 2005, 1/50th scale tests were performed at SOGREAH’s water tank, which enabled to define the tidal turbine design, study the turbine’s influence on the currents field, characterize the wake and generated turbulence and investigate the impact of a shroud. In 2008-2009, a 1/3rd scale turbine, called “Sabella D03” with a 3 meter diameter rotor was installed at sea, in Odet’s estuary (South Brittany), which was a French premiere. This turbine produced electricity and was fully monitored but not grid-connected. It enabled to validate the turbine’s design and technological principles, study underwater acoustic impacts and test the mechanical resistance. Finally, a CFD study was carried out on a real scale modelling in 2011 in order to know better the flow around the machine and forces applying on it. SABELLA is currently finishing the assembly of its “Sabella D10” full-scale turbine, which has a 10 meter diameter rotor and will be installed at sea in the Fromveur Strait and connected to Ushant Island grid in spring 2015. Tests were already performed on the rotor of this turbine at INSEAN Circulating Water Channel as part of MARINET second call. Thus it will be possible to compare numerical modelling, tank tests and real sea behaviour.

The next development step for SABELLA is a pilot farm in the Fromveur Strait, which should be installed in 2017. It will consist of around four “Sabella D15” tidal turbines, which will have a 15 meter diameter rotor. These turbines will thus be one step bigger, and new rotors will have to be developed and their design optimized. The goal for SABELLA was thus to test this new rotor, and to validate the numerical model from which it was designed.

1.2 DEVELOPMENT SO FAR

1.2.1 Stage Gate Progress

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<td><strong>Stage 1 – Concept Validation</strong></td>
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<tr>
<td>• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)</td>
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<td>• Finite monochromatic waves to include higher order effects (25 –100 waves)</td>
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<td>• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)</td>
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<tr>
<td>• Restricted degrees of freedom (DoF) if required by the early mathematical models</td>
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<tr>
<td>• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)</td>
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<tr>
<td>• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable</td>
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<td>• Real seaway productivity (scaled duration at 20-30 minutes)</td>
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<td>• Initially 2-D (flume) test programme</td>
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<td>• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them</td>
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<tr>
<td>• Evidence of the device seaworthiness</td>
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<td>• Initial indication of the full system load regimes</td>
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<td><strong>Stage 2 – Design Validation</strong></td>
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<td>• Accurately simulated PTO characteristics</td>
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<td>• Performance in real seaways (long and short crested)</td>
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<tr>
<td>• Survival loading and extreme motion behaviour.</td>
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<td>• Active damping control (may be deferred to Stage 3)</td>
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### STAGE GATE CRITERIA

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<tr>
<th>Status</th>
<th>Device design changes and modifications</th>
<th>Mooring arrangements and effects on motion</th>
<th>Data for proposed PTO design and bench testing (Stage 3)</th>
<th>Engineering Design (Prototype), feasibility and costing</th>
<th>Site Review for Stage 3 and Stage 4 deployments</th>
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</tbody>
</table>

**Stage 3 – Sub-Systems Validation**

- To investigate physical properties not well scaled & validate performance figures
- To employ a realistic/actual PTO and generating system & develop control strategies
- To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag
- To validate electrical supply quality and power electronic requirements.
- To quantify survival conditions, mooring behaviour and hull seaworthiness
- Manufacturing, deployment, recovery and O&M (component reliability)
- Project planning and management, including licensing, certification, insurance etc.

**Stage 4 – Solo Device Validation**

- Hull seaworthiness and survival strategies
- Mooring and cable connection issues, including failure modes
- PTO performance and reliability
- Component and assembly longevity
- Electricity supply quality (absorbed/pneumatic power-converted/electrical power)
- Application in local wave climate conditions
- Project management, manufacturing, deployment, recovery, etc
- Service, maintenance and operational experience [O&M]
- Accepted EIA

**Stage 5 – Multi-Device Demonstration**

- Economic Feasibility/Profitability
- Multiple units performance
- Device array interactions
- Power supply interaction & quality
- Environmental impact issues
- Full technical and economic due diligence
- Compliance of all operations with existing legal requirements

### 1.2.2 Plan For This Access

This project has several objectives.

#### 1.2.2.1 Device design changes and modifications

One goal of this access was to test a new rotor. Compared to the previous ones, this “Sabella d15” rotor has 5 blades instead of 6, a progressive chord law, a different twist, a different bulb shape, etc. The tests should thus allow checking that this new design enables to achieve a better efficiency.
1.2.2.2 Data for proposed PTO design and bench testing
The tests will allow obtaining forces applying on the rotor on the one hand, and optimal TSR providing maximum efficiency on the other hand. These data will be useful to design the electrical generator that will be used for these turbines and for the control-command of the device.

1.2.2.3 To investigate physical properties not well scaled & validate performance figures
One objective of this access is to validate the numerical model that led to the rotor design, in order to recalibrate it if necessary so that it can be used for any rotor for any specific site.

1.2.2.4 Economic Feasibility/Profitability
With the validation of the rotor performance, economic studies will be led to improve the financial model expected for the multiple units’ array project.

1.2.2.5 Multiple units performance
One part of this access was dedicated to near wake measurement. This will be a very important input for the modelling of multiple devices arrays.

1.2.2.6 Device array interactions
Based on the near wake measurements, calibration of the numerical model will be possible and thus it will allow learning about near wake, far wake and device interactions.

2 OUTLINE OF WORK CARRIED OUT

2.1 Setup

2.1.1 Performance and efforts tests

2.1.1.1 Tests configuration
The first part of the tests consisted in performance and forces analysis. The setup used for these tests is shown in Figure 1. It is a classical setup that is commonly used for propeller testing, with some specificities for tidal turbine tests. The same setup has already been used for the first tests carried out at INSEAN Circulating Water Channel within MARINET second call.
Figure 1: tests setup

A dynamometer is connected to the rotor and controls its rotation speed while measuring torque and force along x axe. A fairing, called dummy nacelle, is installed around the dynamometer axis to simulate the nacelle. As this nacelle is fixed and does not rotate with the rotor and dynamometer, only an upstream current can be simulated. The angle between the current direction and the turbine axis can be modified. The depth of the dynamometer can be modified in order to study the free surface effect.

2.1.1.2 Input parameters

The rotor model diameter is 500 mm, simulating a 15 meter diameter rotor with a 1/30th scale.

The channel contains freshwater, with a density of 1 000 kg/m³. The water temperature is not constant and is measured every day in order to calculate the viscosity.

2.1.1.3 Outputs

The following parameters can be obtained from the dynamometer:

- Force along x axis, thrust, (Fx), measured
- Torque (Q), measured,
- Rotation speed (RPM), measured
- Dimensionless thrust (k_t), calculated \( k_T = \frac{T}{\rho n^2 D^4} \)
- Dimensionless torque (k_Q), calculated \( k_Q = \frac{Q}{\rho n^2 D^5} \)
- Tip Speed Ratio (TSR), calculated \( TSR = \frac{\omega R}{V} \)
- Advance coefficient (J), calculated \( J = \frac{\pi}{TSR} \)
- Reynolds number (Re), calculated \( Re = \frac{\sqrt{V^2 + (\omega 0.7 R)^2} \cdot \rho}{\nu} \)
For each case (one configuration, one current velocity, one rotation speed), around thirty seconds of data are acquired, with a 500 Hz frequency, which provides around 15,000 values per parameter per case. The values averaged over these thirty seconds are then used for the study.

### 2.1.2 Wake measurements

The second part of the tests consisted in an analysis of the near wake field of the turbine by using Particle Image Velocimetry. A photo of the setup during the calibration of the system is shown in Figure 2. Measurements are made for a phase step of 4°. Several TSR have been considered. The PIV system consists of a 200 mJ Nd-Yag lasers and two 11 Mpx Cameras in a stereo configuration looking at the measurement plane through the facility windows. The laser light was delivered to the measurement plane through a window placed in the floor of the test section. The flow has been seeded with hollow glass particle and an area of about 300 x 400 mm² has been analysed.

![Figure 2: PIV setup calibration](image)

### 2.2 Tests

#### 2.2.1 Performance and efforts tests

The dynamometer rotation speed (in RPM) is controlled in order to test a range of Tip Speed Ratios (TSR). A range of TSR from 0 to 6.5 was tested. For an angle of 0°, measurements were made with current velocities of 0.75 m/s, 1.5 m/s, 2 m/s, 2.25 m/s, 2.5 m/s. For the other angles, measurements were made with current velocities of 2.25 m/s and 2.5 m/s. Advance coefficients and rotation speeds for the different current velocities investigated corresponding to the chosen range of TSR are shown in Table 1.
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<td>372</td>
<td>497</td>
<td>559</td>
<td>621</td>
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</tbody>
</table>

Table 1: summary of rotation speeds and current velocities investigated

Several angles between current direction and turbine axis were tested: 0°, 2.5°, 5°, 7.5°, 10° and 15°.
For an angle of 0°, several dynamometer depths were investigated: 62.5 cm, 70 cm and 82.5 cm. For the other angles the dynamometer was always at a 70 cm depth.
Finally, one set of tests without blades was carried out in order to know the blades contribution to the efforts on the turbine.
A summary of the tests undertaken is shown in Table 2.
Table 2: matrix of completed tests

2.2.2 Wake measurements
PIV measurements were made for a current velocity of 2.5 m/s and for five different TSR:
- TSR = 3, corresponding to maximum efficiency;
- TSR = 4.6, for CFD calibration;
- TSR = 3.8, corresponding to maximum Ct;
- TSR = 2, corresponding to stall;
- TSR = 5.4, a point where the turbine is “singing”.

For each TSR, 300 images were made for each phase, which means 11 610 images per TSR. For some phases, more precise acquisitions were made, with 1 000 images instead of 300, in order to have more data about turbulence.

2.3 Results

The main results of the tests are presented below. It should be noted that a more precise analysis of the results is still being carried out.
2.3.1 Influence of the angle on the efficiency

SABELLA’s turbines blades have no pitch and are thus not able to follow current direction variations. This is why the rotor should be tolerant to variations of angle between current direction and turbine axis, as the tidal currents are rarely perfectly bi-directional.

Previous tests carried out at INSEAN on “Sabella D10” rotor showed that an angle between rotor axis and current direction of up to 5° did not bring any loss of performance, and that for an angle of up to 10° the loss of performance was very small. For “Sabella D15”, measurements were made for more angles: 0°, 2.5°, 5°, 7.5°, 10° and 15°, in order to have a precise idea of the change of performance with small variations of current direction. The differences of performance for these angles compared to an angle of 0° are shown in Figure 3.

It can be seen that the efficiency increases slightly between 0° and 5°, and that the best efficiency is achieved for an angle of 5° (+0.6%). The efficiency then decreases linearly until an angle of 15°. For an angle of 10°, the loss of efficiency remains small: 1.4%. For an angle of 15° the loss of efficiency is 3.3%.

![Figure 3: difference of performance for different current angles compared to 0°](image)

These results are logical as the design of the rotor has been made for an angle between current direction and rotor axis of 5°. This is indeed the angle that will actually be seen by the “Sabella D15” turbine in the Fromveur Strait.

2.3.2 Comparison with CFD study

A CFD study had been done to design the rotor. One goal of the tests was to validate and calibrate the CFD study. Figure 4 shows the Cp obtained with the tests and with the numerical study. It can be seen that the efficiency has been overestimated in the CFD study, but that the two curves have the same patterns. There are several explanations for this overestimation:

- scale effects (simulation of a full scale turbine vs a model scale turbine);
- influence of the free surface (closer in tank tests than in reality);
- influence of the turbulence;
- Reynolds number range...

More numerical runs are currently being done in order to understand these differences and recalibrate the model.
The optimal TSR however is very close in both cases, only slightly overestimated in the CFD study.

2.3.3 Near wake of the turbine

PIV measurements resulted in a huge amount of data, and especially photos, that need to be post-processed before being analysed. This post-processing and following analysis will be conducted in the following months and the results should be available mid-2015. An example of the results obtained is provided in Figure 5.
2.4 ANALYSIS & CONCLUSIONS

2.4.1 Impact of Reynolds number

So that tank tests are relevant, the Reynolds number should be in the same range as in reality in order to have the same type of flow. The Reynolds dimensionless number is calculated for a propeller using the following formula:

\[ Re = \frac{V (V^2 + (\omega R)^2)^{1/2}}{\nu}, \]

where \( V \) is the current velocity (m/s), \( \omega \) is the rotor rotational speed (rad/s), \( R \) is the rotor radius (m), \( c \) the blade chord (m) and \( \nu \) the water cinematic viscosity (m²/s).

At full scale, the order of magnitude of Reynolds number is a few millions. For these tests, the maximum current velocity used is 2.5 m/s, so such a high Reynolds number cannot be reached. It is thus important to check that the tests are done in the correct flow regime. For this, tests have been done at several current velocities, with no angle between current direction and rotor axis. The efficiencies for these tests are gathered in Figure 6. It can be seen that the efficiency is much lower for a current velocity of 0.75 m/s than for the other velocities. From a current velocity of 1.5 m/s, the efficiency does not change anymore with an increase of current velocity. It can thus be assumed that a current velocity higher than 1.5 m/s allows reaching a high enough Reynolds number. Most of the tests having been done at current speeds of 2.25 and 2.5 m/s, it can be considered that the results can be exploited in a correct similitude way.
2.4.2 Free surface effect

Because of the length of the dynamometer arm, the turbine cannot be tested at a depth equivalent to real sea conditions, as SABELLA’s turbines are seabed-mounted. Thus there could be free surface effects impacting the results. In order to check this, tests were made with no angle between current direction and rotor axis with three different depths. The $C_p$ for these three tests are shown in graph Figure 7.

The efficiencies for these three different depths are very similar, and the differences in the useful range of TSR are within the dynamometer measurements precision range. Thus it can be concluded that there is no free surface effect and that the model is deep enough during all tests.
3 MAIN LEARNING OUTCOMES

3.1 PROGRESS MADE

3.1.1 Progress Made: For This User-Group or Technology

3.1.1.1 Progress made vs Plan
One part of the Plan was “device design changes and modifications”. Tests have been carried out on a newly designed rotor scaled from a “Sabella D15” turbine. The tests did not show a performance as good as expected but a careful study of the tests and numerical results will enable a better understanding of the physical phenomena and a recalibration of the numerical model and of the tests results, which will be very helpful for the design of future rotors.
Second and fourth goals of the Plan were to obtain “Data for proposed PTO design and bench testing” and “Economic Feasibility/Profitability”. Important progress has been made on these points. The tests indeed allowed knowing the optimal TSR for achieving the highest efficiency, and forces on the rotor for the different TSR are now known. This will be very useful for the design of the electric generator, the control-command of the whole device and calculation of actual energy production.
A third aim was to “investigate physical properties not well scaled and validate performance figures”. As explained above, the performance figures from the numerical model could not be validated as such, but a recalibration of the numerical model is being carried out so that it can be used for any rotor for any specific site.
The last goals were to acquire data for “multiple units’ performance” and “Device array interactions”. For this, near wake measurements have been carried out and are currently being post-processed and investigated. They will be a very important input for the modelling of multiple devices arrays.
3.1.1.2 Progress made for the Technology

Several important points have been learned regarding “Sabella D15” tidal turbine’s rotor. First, the tests allowed knowing the maximum hydrodynamic efficiency the rotor can reach, and at which TSR it achieves it. Moreover, torque and thrust acting on the rotor have been evaluated. Furthermore, the tests confirmed that the best efficiency is achieved for an angle between current direction and rotor axis of 5°. The performance is slightly lower when the angle decreases to 0° or increases to 10°, and drops more for an angle of 15°. The rotor was indeed designed for an angle of 5°, as this is what the turbine will see in the Fromveur Strait.

Moreover, the tests will allow to recalibrate the CFD model. Several paths will be investigated for this: difference of turbulence between model and channel, scale effects, channel blockage effects, free surface effects, etc. Finally, the near wake of the rotor, around the nacelle, will be available, which will be very useful for the mechanical dimensioning and for the turbines arrays studies.

3.1.1.3 Next steps for Research or Staged Development Plan

Following steps are planned in the next few months. First, results from the previous tests carried out on “Sabella D10” turbine will be compared to the real sea behaviour. This will allow a complete understanding of the numerical results and of the channel tests. Thus, the numerical model will be recalibrated and the difference between channel tests and real sea behaviour will be estimated for “Sabella D15”.

Moreover, an important step in the design of the “Sabella D15” tidal turbine will be to carry out mechanical studies, based on the hydrodynamic efforts obtained from the tests. This might lead to change the rotor design, implying new numerical studies, in an iterative process.

Furthermore, the tests have been done on the rotor only so far. A next step will thus be to design the gravity based foundation of the turbine. Its influence on the rotor could be characterized either by new numerical studies or by tank tests.

The influence of swell on the turbine behavior, performance and structure will also have to be investigated. This will be done by carrying out new tests, either in a wave tank that can also produce current or in a towing tank.

Finally, tidal turbines arrays will have to tested, in order to know the influence of a turbine on another and to determine the best array pattern. For this, tests will have to be done, possibly at INSEAN Circulating Water Channel.

3.1.2 Progress Made: For Marine Renewable Energy Industry

- The setup used for the performance and forces tests was good and can easily be reused for future tidal turbines rotors tests.
- The setup used for the PIV measurements was complicated. It was the first time this precise setup was used. It appeared difficult to place correctly one of the cameras providing the tangential component of the velocity, resulting in non-satisfying images due to the thick windows of the facility that were introducing strong optical aberrations. One should thus plan enough time for the set-up of PIV measurements because technical solutions to overcome the problem exists (underwater cameras and laser for example). INSEAN Circulating Water Channel is now aware of the problem and knows how to carry out such measurements next time, which was not possible in this case because of a lack of time.

3.2 Key Lessons Learned

- Tests should be planned well in advance and should be well defined so that they are prepared correctly.
- Tests should be defined with considerations of the facility test configuration.
- Setup preparation, calibration and validation for wake measurements are very long. This should be taken into account when planning the tests.
4 FURTHER INFORMATION

4.1 SCIENTIFIC PUBLICATIONS

No scientific publication has been made yet. However, publications are expected in the coming year, about the tests themselves and about comparisons between INSEAN and/or SABELLA numerical studies and tests in the Circulating Water Channel.

For information, following previous tests carried out by SABELLA at INSEAN, some publications have been made.

- Experimental investigation of the wake of a horizontal axis tidal current turbine by LDV, at the ReNew Conference in Lisbon, 24-26th November 2014 (Morandi, et al., 2014)
- A paper has also been submitted to IJOME for its special edition on MARINET program. The title of the paper is “Experimental investigation of the wake of a horizontal axis tidal current turbine at different operating conditions”.

Another paper will also be submitted to the European Wave and Tidal Energy Conference (EWTEC) that will be held in Nantes in September 2015. It will present the results of a computational model developed by INSEAN to analyse the hydrodynamic performance of tidal turbines, validated by comparisons with experimental data from the previous tests carried out by SABELLA at INSEAN.

4.2 WEBSITE & SOCIAL MEDIA


YouTube Link(s): [https://www.youtube.com/channel/SabellaTidal](https://www.youtube.com/channel/SabellaTidal)

LinkedIn / Twitter / Facebook Links: [www.linkedin.com/company/sabella](http://www.linkedin.com/company/sabella) / [https://twitter.com/SabellaTidal](https://twitter.com/SabellaTidal) / [www.facebook.com/SabellaTidal](http://www.facebook.com/SabellaTidal)

5 REFERENCES


6 APPENDICES

6.1 STAGE DEVELOPMENT SUMMARY TABLE

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.
## Development Protocol

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## Objectives/Investigations

- **Op. Verification**
  - Design Variables
  - Physical Process
  - Validate/Calibrate
  - Math Model
  - Damping Effect (Signal Phase)

## Output/Measurement

- **Vessel Motion Response Amplitude Operators & Stability**
- **Pressure Force, Velocity RAOs with Phase Diagrams**
- **Power Conversion Characteristic Time Histories**
- **Hull Seaworthiness, Excessive Rotations or Submergence**
- **Water Surface Elevation Abilities of Devices**

### Primary Scale (λ)

- \( \lambda = 1: 25 - 100 \) (\( \lambda = 1 : 5 - 10 \))
- \( \lambda = 1: 10 - 25 \)
- \( \lambda = 1: 2 - 10 \)
- \( \lambda = 1: 1 \), Full size

### Facility

- **3D Flume or 3D Basin**
- **3D Basin**
- **Power Electronics Lab**
- **Beam Site**
- **Sheltered Full Scale Site**
- **Exposed Full Scale Site**
- **Open Location**

### Duration (inc Analysis)

- **1-3 months**
- **6-12 months**
- **6-18 months**
- **12-36 months**
- **1-5 years**

### Typical No. Tests

- **250 - 750**
- **250 - 500**
- **100 - 250**
- **100 - 250**
- **50 - 250**
- **50 - 250**
- **Full Commercial**
- **Statistical Sample**
- **10,000 - 20,000**
- **2,500 - 5,000**

### Budget (€,000)

- **1 - 5**
- **25 - 75**
- **50 - 250**
- **1,000 - 2,000**
- **10,000 - 20,000**
- **10,000 - 20,000**
- **2,500 - 5,000**

### Device

- **Idealised with Quick Change Options**
- **Simulated PTO (0-50 m) Damping Range & Mooring & Mass Distribution**
- **Power Control & Mooring system Scenarios**
- **Survival & Operating Scenarios**
- **Full Scale Tests**
- **Overall System Simulations**
- **Pre-Production**
- **Pre-Commercial**
- **Operational Multi-Device**

### Excitation/Waves

- **Monochromatic Linear (10-25A/m) Waves**
- **15 Classical Seas Spectra**
- **50 Classical Seas Spectra**
- **Long Short Crested Seas**
- **Long Crested Head Seas**
- **Deployment Site Site Sea Spectra**
- **Extended Test Period**
- **Full Scatter Diagram for initial Evaluation**
- **Time & Frequency Domain Analysis**

### Specials

- **Darms (Fk only)**
- **1-Dimensional Waves & Multi Hull**
- **Short Crest Seas Angled Waves**
- **As Required**
- **Fine Waves Applied Damping**
- **Multi-Freq Inputs**
- **Power Take-Off**
- **Device Output**
- **Salt Corrosion Marine Growth**
- **Permissions**
- **Quick Release Cable System**
- **Array Interaction**
- **Array Interaction**
- **Market Projection**
- **Small Array (Upgrade to Generating Station)?**

### Math Methods (Computer)

- **Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion**
- **Steady State Solutions**
- **Adaptive Damping**
- **Multi-Variation System**
- **Naval Architects Design Codes for Hull, Mooring & Anchorage System**
- **Economic & Business Plan**
- **Economic Model**
- **Economical Analysis**
- **Grid Simulations**
- **Wave forecasting**
- **Array Interaction**
- **Market Projection**

### Evaluation (Stage Gates)

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6.2 ANY OTHER APPENDICES