Recent developments at CNR-INSEAN on testing and modelling marine renewable energy systems for waves and currents

Hydrodynamic testing centers are nowadays challenged by a continuously increasing demand for studies aimed at the development, verification and assessment of marine renewable energy capturing systems. This paper describes the experience matured over the last years at CNR-INSEAN, the marine technology research Institute of the Italian National Research Council. Originally designed for hydrodynamics testing of marine vehicles, the Institute's experimental facilities like wave and calm water tanks, circulating water channel, now host testing programs on wave energy converters, marine current turbines and hybrid systems, combining devices to extract energy from different marine sources like waves and winds. Selected case studies are described and main findings are discussed in the paper.

DOI: 10.12910/EAI2015-043

F. Salvatore, F. Di Felice, L. Fabbri

Introduction

The next one-two decades will be crucial to the assessment of marine renewable energy as a primary alternative to conventional, environmentally non-sustainable energy sources.
The enormous potential of the energy stored in the oceans is nowadays fully recognised. Nevertheless, in spite of the plenty of concepts, patents, promising prototypes materialised over the last two-three decades, the real possibility to achieve a massive exploitation of marine renewable energy in the short term is still under debate.
The main factors hindering the final affirmation of marine renewables are related to persisting uncertainties about the real cost-effectiveness of energy-generating plants over their whole life-cycle from deployment to final decommissioning. Existing knowledge from few full-scale prototypes deployed at sea highlights contradictory results and, in many cases, unsatisfactory performance in real operating scenarios.
A huge R&D effort is then underway to develop and demonstrate new energy harvesting concepts with enhanced productivity, safety and reliability also in harsh operating conditions, at reduced maintenance and operational costs.
To achieve such challenging objectives, careful studies are necessary from the early stages of the design process. Most of this work is carried out in hydrodynamics testing facilities, where small-scale model devices are analysed, improved and assessed before deploying larger-scale prototypes at sea.
The experience on marine renewable energy technologies matured at CNR-INSEAN, the marine technology research Institute of the Italian National Research Council, is the subject of the present paper. The Institute has an international recognition for fundamental and applied research on marine vehicles and structures. Research and technology

Contact person: Francesco Salvatore
francesco.salvatore@cnr.it

FIGURE 1 CNR-INSEAN facilities for hydrodynamic testing of marine renewable energy systems. From left to right: wave tank, calm-water tank and circulating water channel

support activities take advantage of a network of world-class hydrodynamics testing infrastructures and of theoretical/computational modelling laboratories, where in-house solvers for analysis and design applications are developed.
During the last few years, an increasing amount of R&D work has been dedicated to studies on marine renewable energy systems. Experimental and computational studies address wave energy converters, marine current turbines and hybrid systems, where devices to extract energy from different marine sources like waves and winds are integrated.
Activities are partly funded under national and international research programs, and partly carried out as technology support to private companies and other entities.
Recently, a boost to the involvement of CNR-INSEAN on marine renewables has come from the participation in the collaborative R&D project MARINET (www.fp7-marinet.eu), co-funded by the EU under the Seventh Framework Programme (EU-FP7). In this context, CNR-INSEAN has hosted many experimental programs for the development of marine energy systems and has collaborated to important joint research activities.
An overview of selected activities performed at CNR-INSEAN on testing and modelling marine renewable energy systems is presented in the following pages. The main findings from accomplished work and future research perspectives are also discussed.

Marine energy systems testing facilities at CNR-INSEAN

The experimental facilities at CNR-INSEAN provide a world-class, multi-purpose platform of infrastructures for hydrodynamic testing. A description of these plants, the equipment available and the type of tests that can be conducted therein can be found at www.insean.cnr.it.
Originally designed for hydrodynamics testing of marine vehicles, facilities have demonstrated to be perfectly suited for the analysis of marine renewable energy devices.
In particular, the following three infrastructures:

- Wave towing tank
- Calm water towing tank
- Circulating water channel (or, flume tank)

are utilised for applications to marine renewables technologies (Fig. 1).
These three infrastructures are ranked among the largest hydrodynamics facilities in the world currently available for testing marine energy systems. This makes it possible to use large-size scaled models and perform tests that are fully representative of device operation at full scale.

Marine current devices

Two main natural mechanisms originate currents in oceans and seas. One is related to the Moon's

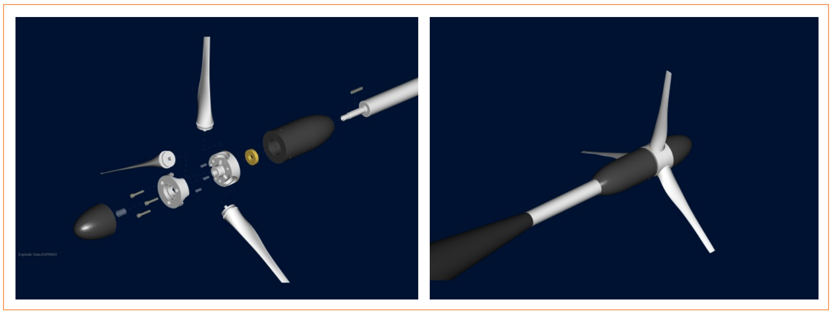

FIGURE 2 CAD model of a three-bladed model turbine built for tests in the flume tank

gravitational effect, which determines a periodic variation of the sea free surface level (tidal range) and yields water flowing from high- to low-tide regions. These currents are referred to as tidal currents and are characterised by a periodic inversion of the direction of the flow. Tidal currents mostly occur close to the coast, with intensity, direction and velocity profile that depend on a combination of local factors.

In other cases, marine currents are generated by gradients of water density due to different temperature or salinity of water masses. Gradient-driven currents typically develop offshore in the oceans (ocean currents) and are uni-directional. A classic example of ocean current is the Gulfstream, where warm waters from the Gulf of Mexico flow up to Polar latitudes along the west coasts of Northern Europe. Both tidal and ocean currents are predictable on a long timeframe with large accuracy.

Marine current energy-capturing devices are classified as "turbine systems," where rotating blades are used to convert water kinetic energy into mechanical energy, and "non-turbine systems", with moving parts consisting of oscillating lifting surfaces (foils, sails or kites) or vibrating cylinders. For details, see e.g. the final report of the 27th ITTC Specialist Committee on the Hydrodynamic Modelling of Marine Renewable Energy Devices [1].

Turbine-like systems represent the most popular technology for marine current energy harvesting. Devices are referred to as Horizontal Axis Current Turbines (HACT) when the rotor axis is aligned to the incoming flow, and cross-flow turbines when the axis is orthogonal to the current direction. Vertical-Axis Current Turbines (VACT) represent a particular case of this type of devices. Both HACT and VACT can be fixed to the sea bottom or floating by surface platforms or submerged structures.

Experience on testing and modelling both horizontal- and vertical-axis current turbines has been matured at CNR-INSEAN over the last few years, in the framework of national research programs as well as under industrial R&D programs funded by private companies. One of the first examples of studies of vertical-axis turbines was performed in 2005-2006, in collaboration with the Italian company developer of the "Kobold" turbine concept [2].

The activity on marine current devices has experienced a dramatic increase during the EU-FP7 MARINET Project (2011-2015), with testing programs on both HACT and VACT, fundamental research and validation of in-house-developed computational models to predict turbine performance.

In support to testing activities, specific know-how has been developed for the design and manufacturing of components of model turbines being tested. Figure 2 shows details of a three-bladed turbine model commissioned by a research team from the Universities of A Coruña and Santiago de Compostela under the MARINET project.

Model turbines tested in both flume and towing tanks have typically diameters of 400-500 mm. Reynolds numbers characterizing the flow around the model rotor are in a critical range (approximately, Re = 10^5), characterized by a laminar flow on blades, that may be not representative of real operating conditions for a rotor with 10-15 m diameter in full scale, where the Reynolds number is 1-2 orders of magnitude higher and a fully-developed turbulent flow occurs around the rotor blades.

To overcome scaling problems, unconventionally large models should be tested. Such a challenging experiment has been performed in fall 2014 at CNR-INSEAN. A 1.5 m diatemer rotor, designed at Queen's

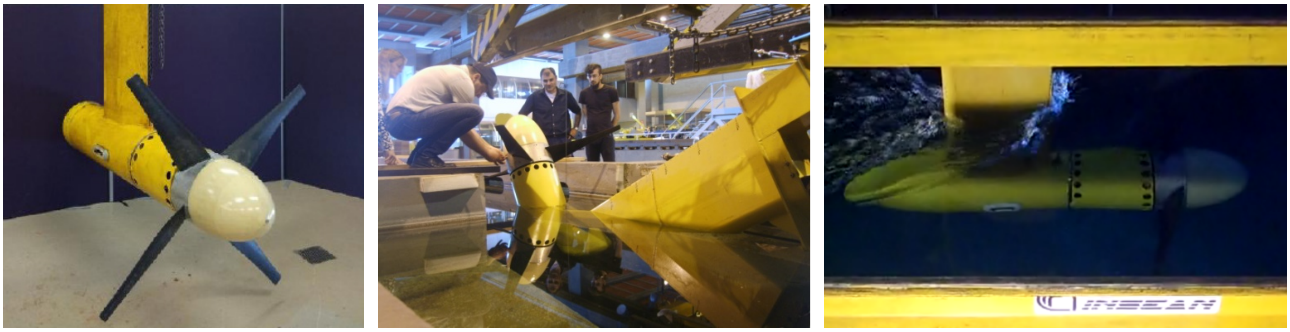

FIGURE 3 The 1.5 m model of a horizontal-axis marine current turbine (INI-TTT project) during set-up and tests in the calm water towing tank at CNR-INSEAN

University of Belfast (INI-TTT Project) for lake and sea trials in Nothern Ireland's tidal sites, has been tested in the large calm water tank. This 460 × 13.5 × 6.5 m facility offers width and depth dimensions suitable for hosting such an exceptionally large device, see Figure 3.

The rotor was tested at variable onset flow speed and immersion depths for different system layouts. Device performance results were determined as delivered thrust, torque and power over a full range of variation of the rotor tip-speed ratio, $TSR = \omega R/V$, where ω and R denote, respectively, rotor angular velocity and radius, whereas V is the inflow speed.

Results from towing tank tests were compared to those collected after years of trials in real tidal flows. Results are of extraordinary importance because the 1.5 m model operated in the towing tank in a Reynolds number range that is fully representative of full-scale operations. Moreover, the comparative analysis made it possible to investigate the effect on the device operation performance in a real tidal environment against the idealised, uniform speed, calm-water, zero inflow turbulence conditions that may be established in a towing tank. Data analysis results are given in [3].

If wind-energy inspired marine turbines like those described in figures 2-3 may represent a conservative design strategy, nonetheless many efforts are devoted to develop concepts that are more tailored to the peculiarities of marine currents. A main challenge is to ensure an adequate power output regardless of the periodic inversion of the flow direction in a tidal environment.

A classic approach is to use vertical-axis current turbines (VACT). Darreius-type turbines, like those in Figure 4, are insensitive to the direction of the inflow. This represents a clear advantage for tidal currents, in that complex and costly systems to adjust rotor blades to the incoming flow directions are made unnecessary. The trade-off is a generally lower power efficiency of VACTs versus HACTs.

FIGURE 4 Examples of vertical-axis marine current turbines (VACT) models tested in the CNR-INSEAN towing tank (Kobold turbine, left), and flume tank (ABENGOA project, right)

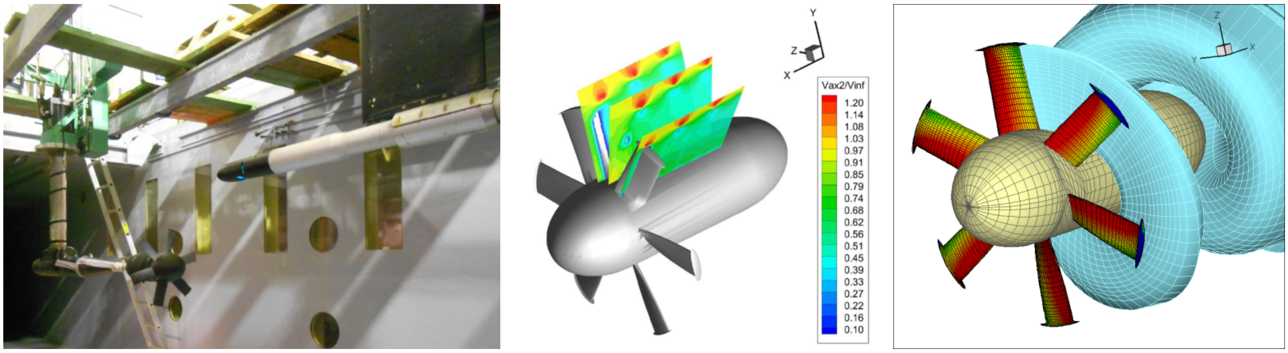

FIGURE 5 SABELLA horizonthal-axis turbine: set-up in the CNR-INSEAN water flume (left), results of wake flow measurements by Laser-Doppler velocimetry (center) and results of CFD simulations (right)

An attempt to realise an unconventional horizontal-axis rotor that can operate in both ebb and flow tidal phases without the need to change the device orientation is the concept developed by the French company SABELLA SAS. The device consists of a conventional HACT (Fig. 5) with blades having bi-directional sectional profiles, that is leading and trailing edges have the same shape. Model tests carried out at the CNR-INSEAN water flume have demonstrated that such a design can operate with power efficiencies of about 40%, that is fully comparable to conventional HACT devices.

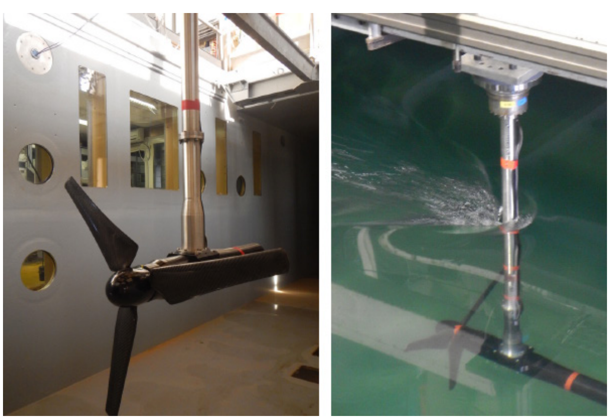

FIGURE 6 The horizontal-axis, 3-bladed rotor designed at IFREMER (France) used in the Round-Robin tests. Pictures show trials at CNR-INSEAN water flume (left) and towing tank (right)

Tests allowed to compare hydrodynamic performance of four alternative rotor designs over a range of operating conditions (TSR and *yaw* angle between shaftline and inflow) and for different device installations (bottom-fixed or floating). In addition to this, a complete rotor wake flow characterization was accomplished using advanced Laser-Doppler Velocimetry (LDV) and Particle-Image Velocimetry (PIV) techniques [4].
The performance/velocimetry dataset collected for the SABELLA rotors is unique for the completeness of information given and represents a fundamental resource for the enhancement of design techniques and tools. The dataset is currently used to perform validation studies of CFD models developed at CNR-INSEAN to predict the hydrodynamic performance of marine current turbines. Preliminary results of this study are presented in [5].
Another aspect worth the effort of dedicated studies is the impact of testing environment on turbine performance estimations. Considering the turbine tests described above, it should be noted that the same type of device, horizontal- or vertical-axis, can be tried in a towing tank as well as in a circulating water channel (or, flume tank). The choice of the type of facility is usually related to practical issues like availability of the infrastructure, dimensions of the model to test, easy installation of the set-up, and so on. Nevertheless, towing or flume tanks may imply different inflow speed ranges and, above all, different inflow turbulence levels.

In this context, in 2014 CNR-INSEAN and other partners of the EU-FP7 MARINET Project have shared the first systematic attempt to address the problem. Specifically, a notional horizontal-axis rotor (design by IFREMER, Fig. 6) was tested across four infrastructures, two towing tanks and two flume tanks. CNR-INSEAN contributed with tests in both types of facilities. Preliminary results of this Round-Robin test presented in [6] document the influence of onset flow turbulence and of other testing conditions on the measured performance of model turbines.

Wave energy conversion

Waves are maybe the most tangible representation of the energy stored inside seas and oceans. As opposed to marine currents, waves are present everywhere but with characteristics like period and elevation that are predictable only with approximations in the short term. As a general rule, ocean waves have a much higher energy potential than that in confined seas like, e.g., the Mediterranean.

The variability of energy resource characteristics explains the great variety of existing energy capturing concepts. The following broad classes can be used to group most technologies, see e.g. [1] for details:

a) *oscillating bodies/point absorbers*: waves induce oscillating motions of floating or submerged bodies, and linear/rotational generators are used to convert motions into electrical power. This type of devices is preferably deployed offshore;
b) *oscillating water columns*: incident waves penetrate a chamber and determine an alternative rise and fall of the free surface therein; this yields reciprocal pumping in/out air from the chamber top and the resulting flux is used to drive Wells turbines connected to generators. This type of devices are suited for onshore installations;
c) *overtopping devices*: floating dam structures are deployed in deep sea areas to focus waves in a restricted area and determine an artificial water rise, whose head is used to move low head turbines.

The hydrodynamic testing of small-scale WEC models in wave basins presents specific challenges. In particular, WECs are characterised by a typically complex interplay between station-keeping properties of the energy capturing system and the dynamics of the power take-off system (PTO). The accurate modelling of the PTO in small-scale devices is difficult as mitigation of passive loads like friction among moving parts is typically hard to be correctly scaled, as described by ITTC [1].

A recent demonstration of WEC testing possibilities at CNR-INSEAN is related to tests of the ISWEC (Inertial Sea Wave Energy Converter) concept developed by a research team from the Technical University of Turin, Italy [7]. This technology is characterised by a wave energy capturing system, based on the gyroscopic effect of oscillating masses. Wave tank tests of a 1:8 scaled model were performed at CNR-INSEAN in 2012, in the framework of a national funding program, see Figure 7 left, and new tests are planned to be carried out in mid-2015. Test data collected so far have been used to validate a RANSE-based Computational Fluid Dynamics (CFD) model to predict device response to incoming wave patterns, see Figure 7 right.

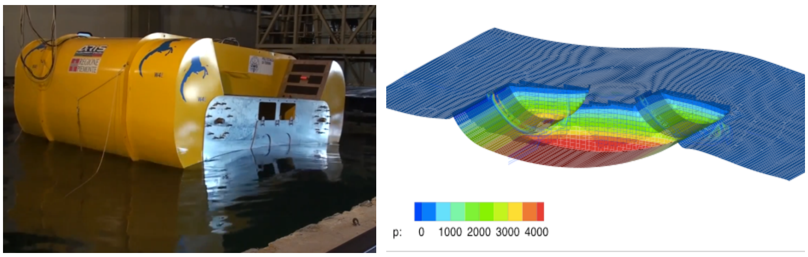

FIGURE 7 The ISWEC wave energy converter: model tests in the CNR-INSEAN wave tank (left) and simulation of station-keeping response by CFD (right)

A recent trend: Hybrid systems

The idea of combining different energy capturing systems into a single device deployed offshore

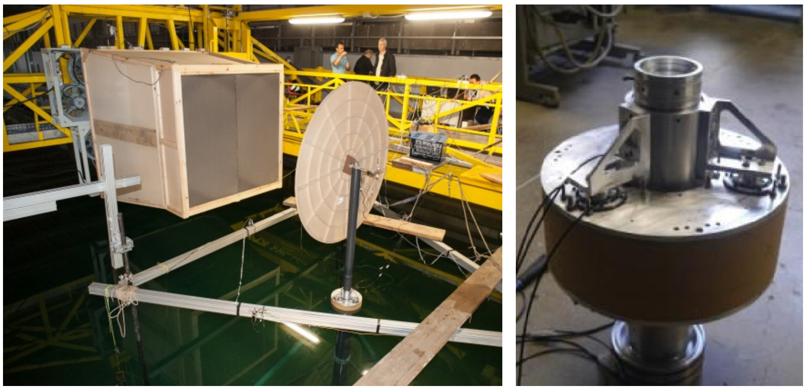

FIGURE 8 Wave tank tests at CNR-INSEAN of the STC system, a hybrid wave/wind energy device. Overview of the set-up with wind generators and nozzle (left) and close-up of the WEC (right)

is considered as a potentially effective strategy to maximise power output capabilities by limiting the investment costs related to the various phases of the device life-cycle.

Systems of this type are usually referred to as “hybrid” systems. The advantages of this solution stem from the possibility to share most of the infrastructure components like platforms, moorings, grid-connection cabling, that support any energy conversion mechanism.

Synergy between wave energy and wind energy systems characterizes the concept developed by a team of Norwegian researchers from CESOS and NTNU. This is the Spar-Torus Combination (STC), which consists of a Spar floating offshore-wind turbine with a torus-shaped heaving body wave-energy converter that can oscillate along the turbine spar.

Numerical simulations of the combined systems showed [8] that the resulting assembly may have a better performance of two separate devices for wave and wind energy harvesting. In particular, the wave absorber has the double effect of producing power and mitigating the intensity of waves impinging at the wind rotor tower. Nevertheless, the combined system is inherently more complex and, hence, it may have a potentially critical behaviour in harsh conditions.

The assessment of structural integrity under extreme operating conditions was the main purpose of a first experimental program on the STC device, conducted at CNR-INSEAN in 2013. A scaled model was manufactured and tested in the wave tank. Wind forcing on the rotor was simulated by using an array of 12 fans inducing a flow with given intensity at the rotor disk through a specifically-designed nozzle. To limit the complexity of the set-up, the wind rotor was simulated by a dummy disk realised with a special porous material. An overview of the set-up during wave tank tests is shown in Figure 8.

System survival tests were performed with a wave-energy device locked in non-operative mode. Alternative survival modes were analysed and compared. Further tests in 2014 were carried out in order to characterise the wave-energy converter power output under a variety of sea- and wind-states. The system PTO was simulated by a sophisticated miniaturised system scaled to the dimensions of the model used in tank tests. Results of tests [9] allowed to determine the power generated for different operating conditions as well as the response amplitude operator (RAO) of the system in station-keeping conditions under waves and wind forcing. Both test programs in 2013 and in 2014 were partly funded under the EU-FP/ MARINET Project.

Concluding remarks and future work

An overview of recent studies on marine renewable energy systems at CNR-INSEAN has been presented. Experimental techniques and computational modelling tools have been developed and are extensively applied for the analysis of the hydrodynamic performance of devices for energy harvesting from waves, winds and marine currents.

Experimental work takes benefit out of a network of testing facilities that are among the largest

worldwide and have a rich equipment with the most advanced measuring systems. In parallel to that, in-house computational models to predict device performance and response to operations at sea are developed and validated through comparisons with results of model tests.
Since 2012, a large part of work in this area has been performed in the framework of the project MARINET, co-funded by the EU under the Seventh Framework Programme (EU-FP7).
Results of experimental studies allowed to achieve a better understanding of the mechanisms of marine energy conversion and gave valuable information to designers as to enhancing systems power generation capabilities.
Experience during model tests also provided new knowledge to improve testing protocols and quantify the effect of different testing environments (towing or flume tanks versus sea trails) on the results of system performance measurements.
The application of non-intrusive measuring techniques, like LDV and PIV to characterise velocity fields around marine turbines as well as in-house developed sensors to render the wave pattern around wave energy converters, gave a comprehensive description of device operation and provided valuable data for the spatial planning of devices in farms or arrays.
Not least, the collection of experimental data into datasets is a fundamental tool for the validation of computational models to predict device performance at the design stage.
In the next years, R&D work on marine renewables is expected to further increase in hydrodynamics testing facilities. CNR-INSEAN aims to face this challenge by pursuing the enhancement of in-house know-how and tools to support the development and assessment of energy-capturing technologies. Collaboration with leading institutes at international level will be hopefully fostered through the participation in joint research projects and international networks.

Francesco Salvatore, Fabio Di Felice, Luigi Fabbri
CNR-INSEAN, Italian Maritime Technology Research Center

references

[1] A.H. Day, I. Penesis, A. Babarit, A. Fontaine, Y. He,M. Kraskowski, M. Murai, F. Salvatore, H.K. Shin, Final Report of the 27th ITTC Specialist Committee on Hydrodynamics Testing of Marine Renewable Energy Devices and Recommended Guideline 7.5-02-07-03.9: Model Tests for Current Turbines, Twenty-seventh ITTC Conference, Copenhagen, Denmark, September 2014.

[2] G. Calcagno, F. Salvatore, L. Greco, A. Moroso, H. Eriksson, Experimental and Numerical Investigation of an Innovative Technology for Marine Current Exploitation: the Kobold Turbine, ISOPE 2006 - Sixteenth International Offshore and Polar Engineering Conference, San Francisco, California, USA, May 28-June 2, 2006.

[3] P.Jeffcoate, B. Elsaesser, C. Boake, F. Salvatore, Effect of submergence on tidal turbine performance, 11th EWTEC Conference, Nantes, France, September 2015.

[4] B. Morandi, G.P. Romano, D. Dhomé, J.C. Allo, F. Di Felice, M. Costanzo, Experimental investigation of the wake of an horizontal-axis tidal current turbine, First Int. Conference on Renewable Energies Offshore (ReNew 2014), Lisbon, Portugal, October 2014.

[5] F. Salvatore, F. Di Felice, D. Dhomé, J.C. Allo, Validation of a computational hydrodynamics model for horizontal-axis marine current turbines, 11th EWTEC Conference, Nantes, France, September 2015.

[6] B. Gaurier, G. Germain, J.V. Facq, C.M. Johnstone, A.D. Grant, A.H. Day, E. Nixon, F. Di Felice, M. Costanzo, Tidal Energy Round Robin Tests: comparisons between towing tank and circulating tank results, Manuscript submitted to *Int. Journal of Marine Energy*, September 2014.

[7] G. Bracco,E. Giorcelli, G. Mattiazzo, E. Tedeschi, M. Molinas , Control Strategies for the ISWEC Wave Energy System, 9th EWTEC Conference, Southampton, U.K., 2011.

[8] M.J. Muliawan, M. Karimirad, T. Moan, Z. Gao, Extreme responses of a combined spar-type floating wind turbine and floating wave energy converter (STC) system with survival modes, in *Ocean Engineering*, vol. 65, pp. 71-82, 2013.

[9] L. Wan, Z. Gao, T. Moan, C. Lugni, Numerical and experimental comparisons of two model tests in different testing facilities of a combined wind and wave concept, Manuscript submitted to *Coastal Engineering Journal*, 2015.