Experimental and numerical investigations on renewable energies at CNR-INSEAN: Challenges and future perspectives

The exploitation of renewable energies from the oceans requires an interdisciplinary approach to solve all the problems linked to a hostile environment and to the need to limit the frequency of operations and maintenance processes. The development of renewable energies from the sea relies not only on classical mechanical, electrical, electronics, control and systems engineering but also on material engineering and on hydrodynamics and fluid structure interaction science. CNR-INSEAN contributes to the latter two

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The exploitation of renewable energies from the oceans requires an interdisciplinary approach to solve all the problems that are linked to a hostile environment and to the need to limit the frequency of operations and maintenance processes.
The development of renewable energies from the sea relies not only on classical mechanical, electrical, electronics, control and systems engineering but also on material engineering and on hydrodynamics and fluid structure interaction science. CNR-INSEAN, the Marine Technology Research Institute at the Italian Research Centre, has an almost centenary experience in these latter two fields and is now active in sustainable exploitation of the marine environment, providing its support to overcome the challenges posed by these new technologies.
The main marine renewable energy sources are offshore wind,

tides, ocean currents and waves. The estimated power of the oceans is 2 million TWh/y [1] but only a very small part of it is harvested at the moment. To enlarge the quantity of energy that can be actually extracted, it is necessary to overcome some of the technological challenges that each one of the different resources implies.

The research work at CNR-INSEAN supports technology developers with the most advanced expertise and capabilities in model testing and computational modelling of device hydrodynamics.

In particular for the experiments, it is possible to use large-scale facilities as the circulating water channel (10m*x*3.6m*x*2.2m test section), the towing tank n. 1 (470m*x*13.5m*x*6.5m) and the towing tank n. 2 (220m*x*9m*x*3.6m) equipped with a wavemaker.

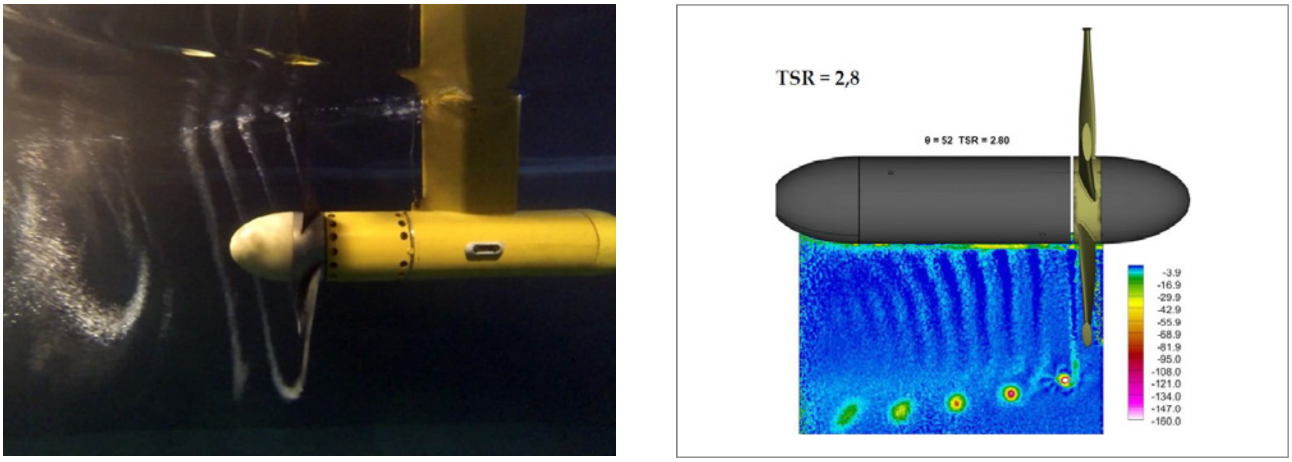

Fig. 1 Left: Air entrained by the tip vortex of a 1.5 m diameter model turbine during towing tank test; Right: Vorticity distribution in the wake of a SABELLA model turbine from PIV measurements in the Circulating Water Channel [2]

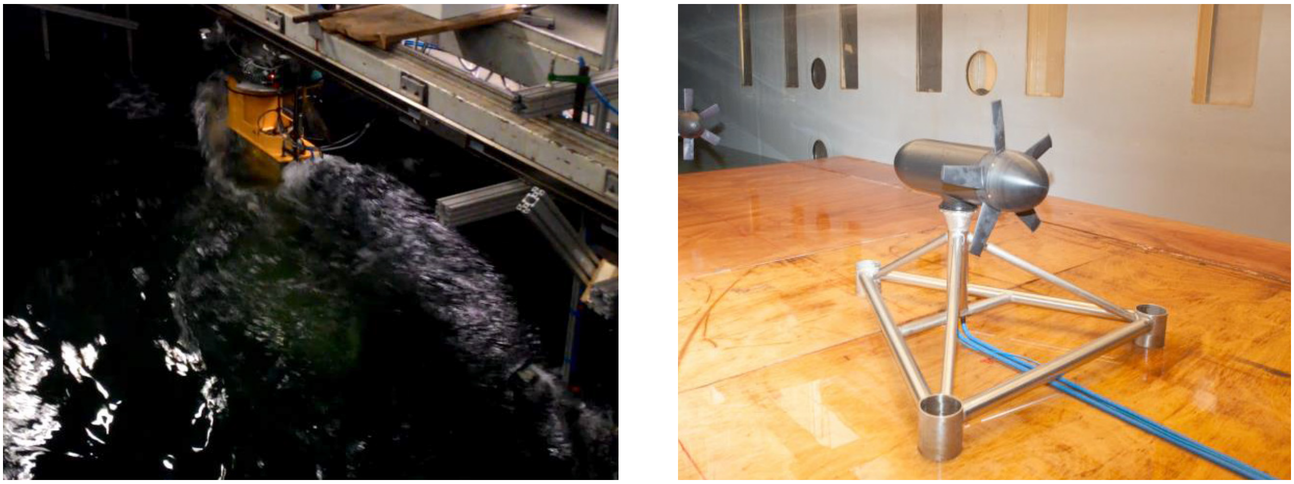

Fig. 2 Left: 1.5 m diameter model turbine during wave/current interaction tests in the wave tank (Courtesy Schottel Hydro GmbH); Rigth: Two 0.4 m model turbines during simulated turbine operation in array in the Circulating Water Channel (Courtesy SABELLA SAS)

In the following, selected contributes of CNR-INSEAN to research in this field are detailed.

Tidal energy concepts

At CNR-INSEAN, tidal turbines in different layouts are developed in collaboration with the most important test centers, and specific test protocols are proposed to the community as new standards. Activities are carried out within research projects as EU-FP7 MaRINET and H2020 MaRINET-2, and commercial projects with key industrial players as SABELLA, Schottel-Hydro, Abengoa.
Most efforts are spent to test devices in conditions that are as much as possible representative of the real environment of a tidal site. The hydrodynamics of medium sized marine current turbine models (Figure 1) are deeply addressed in the circulating water channel. There, single turbine performance, as well as the effect of the flow misalignment, the turbine submergence and the sea bottom proximity on loads are addressed. Energy conversion mechanisms are investigated through the turbine wake flows characterization (right plot of Figure 1) by applying state-of-art velocimetry techniques (LDV, PIV, Stereo-PIV).
Wave tank no. 2 is suited to investigate the effect of waves impinging onto the towed turbine. In particular, measurements are performed to assess the wave-forcing of the blades and of the floating structure (Left, Figure 2).
Towed large-scaled models in complex array configuration are studied in the towing tank no. 1 in calm water conditions.
The device reliability over the life-cycle is assessed with limited uncertainty on the risks associated to commercial projects. The array planning and the device operating points can be determined at relatively low costs and time, before stepping over into deployment of full-scale units at sea (Right, Figure 2).
The development and application of computational hydrodynamics models is complementary to the

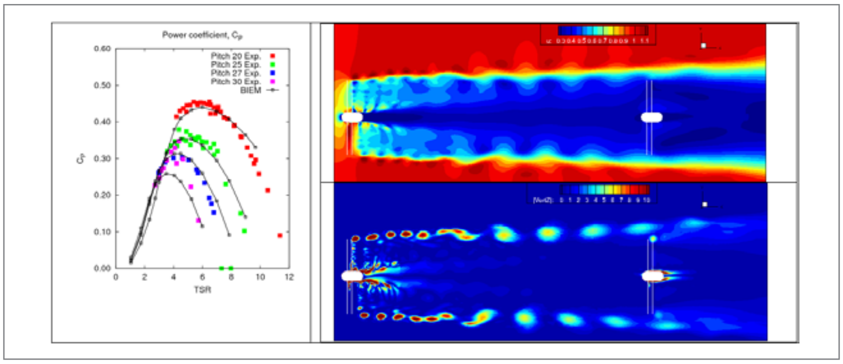

Fig. 3 Left: Turbine performance predictions by BIEM, power coefficient predictions for different blade pitch settings [3]; Right: Computational study by Hybrid RANS/BIEM model of flow around two coaxial turbines spaced d = 4 diameters. Instant axial velocity (top) and vorticity intensity

experimental work at the CNR-INSEAN.
Variable-fidelity models are developed according to the hydrodynamics investigated. Blade Element and Boundary Integral Equation Methods-based computational tools with results validated by using dedicated benchmark data (Left, Figure 3) provide fast and robust predictions envisaged in the preliminary design and optimization of single rotors.
A variety of viscous-flow solvers based on the numerical solution of the Navier-Stokes equations with turbulence modelling (RANS, DES, LES) allows a deep investigation of the turbulence effects on the fluid-dynamics of the turbine. In this case, high-performance computing resources are used to simulate experiments.
A new computational tool based on hybrid N-S/BIEM models is used to analyse turbine wakes and turbine/turbine interactions in arrays (Right, Figure 3). Inherent limitations due to the complexity of studying tidal arrays by physical tests in hydrodynamic facilities are expected to be overcame by the use of such a new computational tool.

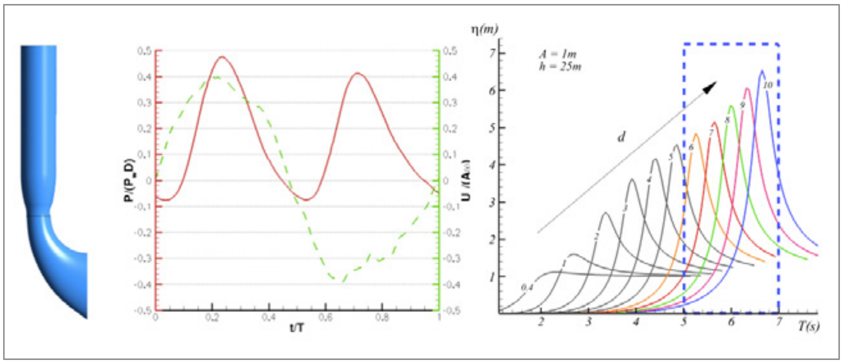

Fig. 4 Left: Sketch of the WaveSax geometry; Centre: Experimental extracted power, made non-dimensional by the wave power correspondent to the device width, and velocity of oscillation inside the device made non-dimensional by the wave amplitude multiplied by wave period; Right: Effect of the immersion as a function of the deployment site

A wave energy concept

Numerical and experimental investigations have been performed on a new technology of Oscillating Water Columns (OWC), the WaveSax. The name of the machine comes from its shape; it resembles a saxophone semi-immersed in the water to "play" the waves. As shown in the first plot of Figure 4, the bell of the sax is immersed into the water and it captures the movement of the fluid particles below the free surface [4].
It is thought to exploit a resonant phenomenon that was first studied for artificial islands, practically a partially immersed hollow cylinder can cause a resonant effect that amplifies the incoming wave inside the cylinder itself. This amplification is looked for to increase the velocity of the oscillating flow across the sax and above all trough its bow, where a Wells turbine is positioned.
Differently from the classical OWC, here the turbine does not make use of the air-flow but of the water-flow, so it is invested by a flow with higher density than the air but at a smaller velocity because of a geometrically-limited Venturi effect.
The use of the Wells turbine allows the extraction of energy in both the directions of motion of the flow across the turbine as shown in the second panel Figure 4, where the instantaneous extracted power and the velocity of water inside the WaveSax are plotted in the wave period.
Numerical and analytical analyses complete the experimental studies, an analytical study can be carried on to increase the performance of this OWC as a function of the deployment site. The third panel of Figure 4 shows the effect of the WaveSax immersion *d* on the amplification of the water oscillation and of the incoming wave period. Once the deployment site has been chosen and the features of the characteristic waves are known, the immersion of the device can be chosen to maximize the resonance in the region of interest as the box highlighted in the plot.
Moreover the numerical studies allow to take into account the effect of vertical surfaces that are positioned just behind the device as harbours structures, in that case the reflections of the waves by the solid surface increase the amplification by up to 40% if a suitable geometry is chosen, that is the extracted power almost doubles.

A concept of hybrid wind and wave energy convertor

Within the EU-FP7 Project "Marinet", CNR-INSEAN has been involved by NTNU-CeSOS in the physical test and numerical simulation of a combined wind and wave energy converter concept, called STC. The prototype is composed by a spar floating wind turbine, moored at the sea bottom through a mooring line and a torus-shaped wave energy converter (WEC) heaving along the spar. The model, which reproduces the prototype in 1:50 scale, has been designed and built at CNR-INSEAN, along with the realization of a complex experimental set-up, necessary to measure the independent motions of the two bodies, the contact forces between the spar and the WEC, and the horizontal loads along the mooring line. Wind forcing was included using a wind drag disc, in order to model the effect of the thrust force on the rotor. The experiments have been conducted in two different configurations: a) with the torus fixed to the spar, to measure the hydrodynamic and the contact forces acting on the torus, both in mean water level and in submerged modes; b) with the torus free to move, with and without the PTO system. Two pneumatic PTO systems in the model reproduce the damping of the corresponding hydraulic PTO in the prototype. Tests in regular and irregular wave, the latter both for operational and survival modes, have been carried out at the wave basin no. 2.

For the configuration a), violent water-entry and exit phenomena, along with green water on deck were observed during the survivability model tests, claiming for a detailed numerical investigation involving complex flows and non-linear physical phenomena. This has required the non-linear numerical model developed at CNR-INSEAN, based on a blended station-keeping potential-flow solver with a local impact solution for bottom slamming events and an approximated model for the water shipped on the deck. This has been validated in several applications in the naval and offshore field, demonstrating its efficiency and ability in reproducing so high complex phenomena even in the STC application.

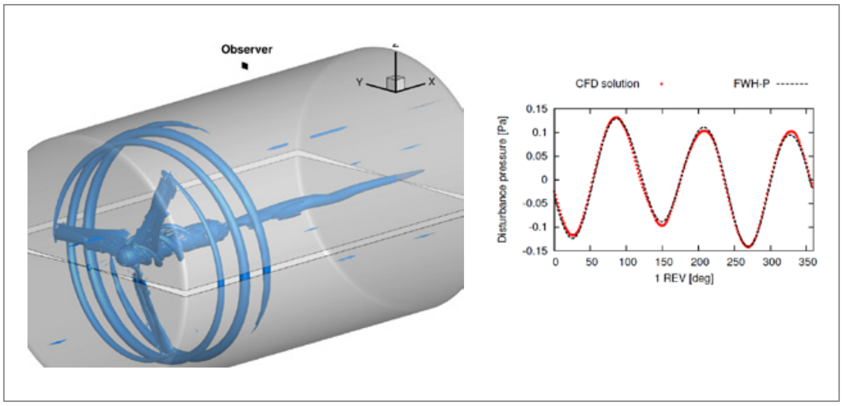

Fig. 5 Left panel: FWH-P surface and vortices core detection; right panel: Acoustic pressure near field

Aeroacoustic Analysis of a Horizontal Axis Wind Turbine Model

Among the many theoretical and numerical models used to predict fluid-dynamically generated noise signatures, the Ffowcs Williams and Hawkings Equation (FWHE) represents a well-known and widely used approach. It extends the Lighthill theory for turbulence generated sound, to account for the presence of solid moving bodies. The noise generation mechanisms are expressed as linear body surface distribution of monopole and dipole and non-linear quadrupole field source terms within a volume of suited extension around the body. The latter contribution may be acoustically relevant for configurations, like Horizontal Axis Wind Turbine (HAWT), characterized by the presence of massive turbulence or vorticity fields. The actual HAWTs have diameter of more than 150 m and more than 7 MW installed power, thus the acoustic impact is an issue.

In this context, the use of the FWHE for porous (fictitious) surfaces (FWHE-P, see left panel of Figure 5) surrounding the body and the corresponding field noise sources is certainly the most suitable and effective way to include the influence of field sources on noise avoiding, at the same time, cumbersome computations of volume integrals. The hydrodynamics features of the flow, representing the sources of noise, are provided by a RANS simulation upon a cylindrical surface rigidly moving (co-rotating) with the blades, chosen as the integration domain of the FWHE-P.A zero-th Boundary Element Method (BEM) is used to solve the integral formulation. The reliability of the predicted acoustic pressure is evaluated by the comparison with the disturbance pressure extrapolated by the near field RANS data, depicted in the right panel of the Figure 5 [6].

Conclusions

The maturity of the concepts extracting renewable energy from the sea is growing in time; some of them are almost ready for the commercial stage, others are still at a concept stage. Nonetheless, all of them still require a large amount of research work from adaptation of the concept to the deployment site to definition of survivability to severe sea conditions, environmental impact and so on. This requires a considerable effort for research to meet these industrial needs.

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