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BOOK OF ABSTRACTS

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Topic 1

Preferential subject A: Grid connection and system aspects of wave and marine current power

Challenges in the Grid Connection of Wave Energy Devices

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Session I, Tuesday 13.50–14.55, Main hall

In considering the grid connection of ocean energy devices, and in particular, the connection of large offshore arrays, there are a number of technical and non-technical challenges that need to be addressed by wave energy device developers. As device developers approach pre-commercial operation, grid connection factors will become increasingly significant in both technical and financial terms. In this paper some generally applicable technical and non-technical challenges are examined. A grid connection costing case study in the Irish context is performed as a practical indicator of these issues.

Keywords: wave energy, grid connection, cost study, generators

Is it a showstopper? Reliability assessment and criticality analysis for Wave Energy Converters

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Session I, Tuesday 13.50–14.55, Main hall

The reliability of wave energy converters (WECs) is a key issue that has to be addressed in order to make them a viable energy option. At this stage of early industrial development the reliability assessment of WECs is a challenging task. In this paper existing reliability methods, namely Reliability Block diagrams, have been applied to a notional configuration. It was found that omnipresent lack of failure rate data makes rather crude adjustments of often generic data necessary which generally lead to rather unfavourable and highly uncertain results. Reliability data is either not available due to sparse field experience or is kept confidential, within different project developments to secure competitive advantages and intellectual property.

In order to foster the progress of the marine energy industry, the reliability of devices must be demonstrated and improved. This requires a joint effort between industry stakeholders to collect, share and disseminate existing failure knowledge and future operational experience.

Keywords: Failure rate adjustment, Marine energy, Reliability assessment, Reliability Block Diagrams

Development of the French Wave Energy Test Site SEM-REV

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Session I, Tuesday 13.50–14.55, Main hall

Progress to date in different stages of the SEM-REV French Wave Energy test site development is highlighted in this paper. The SEM-REV will serve wave technology developers as well as research in hydrodynamics related to wave energy extraction. The test site comprises a 2.5 MVA power cable connected to the national grid through an onshore substation. The off-shore 1 km² test zone is fully instrumented with 2 wave buoys and a matrix of current profilers hence providing continuous wave climate information.

After completing the initial site assessments [1] and defining the regulatory frame, the development of the project is undergoing several consultation phases.

The SEM-REV permitting process is aiming to obtain a consented zone with pre-arranged permits, which will enable developers to operate easily under the site's requirements. Nevertheless, the identified regulatory frame will be a good baseline for project development in French waters.

Assessment of the performance of wave energy converters relies on accurate measurement and knowledge of the wave climate. Additionally, the electrical analysis of the power systems requires accurate process and preparation of the electrical assets to perform different state measurements.

The SEM-REV wave test site planning is taking into account these requirements to prepare detailed performance testing and future certification.

Keywords: wave energy test site, wave energy converter, full-scale demonstration, power assessment

Comparing the electrical transmission systems for Archimedes Wave Swing parks

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Session I (second half), Tuesday 15.10–16.15, Main hall

One way to satisfy the increasing need of clean and renewable energy is to convert the energy of the sea waves into electricity. In this paper Archimedes Wave Swing converters are used to extract energy from the sea and to create various wave parks with an average power of 45 MW. The converters are connected via electrical components in the most suitable way for power transmission to the grid resulting in different topologies. The aim of this paper is to analyze and compare these topologies according to annual energy yield, yearly losses, price and levelised production cost. The results show that economically the most attractive solution is if the Archimedes Wave Swing devices are equipped with back-to-back converters.

Keywords: Archimedes Wave Swing, Wave Energy Conversion, Wave Energy Converter Park

Description of the control and measurement system used in the Low Voltage Marine Substation at the Lysekil research site

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Session I (second half), Tuesday 15.10–16.15, Main hall

This paper gives a description of the control and measurement system inside the Low Voltage Marine Substation at the Lysekil Research site located close to Lysekil on the Swedish west coast. The Lysekil project is run by the Swedish Centre for Renewable Electric Energy Conversion at Uppsala University.

The control and measurement system consists of three PACs, Programmable Automation Controllers, inside the Marine Substation. Each PAC is dedicated to one of the tasks safety and relay-control, DC to AC inversion and data-acquisition. One PAC controls the land based measuring-station. The system has been tested with the control algorithm constant modulation index. The control algorithms constant DC level and constant AC level has been discussed, especial the different behaviour of the algorithms when connected to the grid compared to connected to resistive loads.

Keywords: Control system, Switchgear, Wave power, Inverter

Laboratory Experimental Verification of a Marine Substation

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Session I (second half), Tuesday 15.10–16.15, Main hall

Wave energy is a renewable energy source with vast potential, which could make significant contribution to world electricity demand in the future. In this paper, a way to electrically interconnect wave energy converters into a farm is described. Measurements of voltage and current wave forms in the interconnection of two PM synchronous machines on the common DC-bus of a marine substation are compared with simulations in MATLAB Simulink. It is demonstrated how the generators intermittently deliver power to the common DC-busbar and how the power, after rectification and filtering of the voltage, is continuously extracted in a resistive load. A unique feature of the variable frequency substation at hand is that it will be located on the seabed.

At the Lysekil Research site, where the marine substation will be installed, the DC-bus voltage will be actively controlled by means of an inverter. This will change the damping and hence the absorption width of the linear generator-based WECs that are connected to the substation. The experiments carried out here demonstrate the principle of operation and verifies that the system works as expected.

Keywords: Marine substation, permanent magnet linear generator, experimental verification

Topic 2

Preferential subject B: Future markets and ocean energy financing

The Development of Alderney's Tidal Resource

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Session II, Wednesday 13.30–14.35, Main hall

A large scale commercial tidal power station which could be a world first is to be developed from the large tidal resource in Alderney's waters. Alderney, the third largest Channel Isle, owns its own territorial waters out to the 3 mile limit and has its own government which has enabled it to establish a one-stop, robust consents and licensing procedure to exploit the resource. The Alderney Commission for Renewable Energy was formed specially to oversee and regulate the development of Alderney's renewable energy resources and to ensure an appropriate financial benefit to the Island from their exploitation. Detailed conceptual work by the Commission, a local company, Alderney Renewable Energy Ltd (ARE), and the tidal device developer, Open Hydro, has led to an agreement for ARE to exploit 48 square miles of the territorial waters with a resource of several GW. A first stage is planned to deploy Open Hydro turbines to supply 285 MW to the nearby French grid on the Cotentin peninsula. The remaining territorial waters out to 3 miles and the waters beyond are available for other schemes.

Keywords: Alderney Tidal Project, Licensing

Non-technical barriers to wave energy development, comparing progress in Ireland and Europe

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Session II, Wednesday 13.30–14.35, Main hall

This paper outlined the non-technical barriers to wave energy development, comparing progress in Ireland and Continental Europe. There have been many reports to date examining the subject from a generic perspective, but few have focused on the progress, or lack of it, in individual countries. The report stemmed from existing work carried out by Waveplam partners in Europe and the International Energy Agency, Ocean Energy Systems (IEA-OES). Waveplam is an

EU project supported by Intelligent Energy for Europe (IEE) addressing non-technical barriers that will face the wave energy industry as it moves towards the mass deployment of devices. The framework for discussion comprised three categories of barrier: regulatory, logistical and financial barriers. Each category was assessed with regards its relevance in either the R&D, manufacture or development/production phase of the industry. Results of the analysis showed that most countries had addressed some of the issues. Ireland has made extensive progress with regulatory issues, in particular developing a four phase strategy for product development, as well as specifying targets, but still has not implemented investment grants, a 'one-stop shop' facility for permit applications, easy access to the grid, or suitable construction facilities, skilled workforce, and usable ports. Mainland Europe on the other hand has some natural advantages from a logistical perspective, having larger economies enabling relatively easy industry adaptation to ocean energy construction. Most have population centres located close to the wave energy source, providing better grid infrastructure and construction/port facilities. However the majority of the countries still need to address regulatory issues.

In conclusion, the R&D, manufacturing and development sectors of the wave energy industry present many barriers, with several barriers common to all three. Significant progress has been made by many countries to reduce these barriers. However, there is much inconsistency as to what has been addressed by individual states, with the majority of barriers still remaining to be addressed.

Keywords: Non-technical barriers, wave energy converters

Proposed Internationalisation of the UKERC Ocean (Wave and Tidal Current) Renewable Energy Technology Roadmap

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Session II, Wednesday 13.30–14.35, Main hall

This paper provides an overview of the UKERC technology roadmap and its proposed internationalization. It describes a route for mobilizing the wave and tidal energy community down a deployment pathway towards targets in 2020.

The roadmap is aimed at providing a focused and coherent approach to technology development in the ocean energy sector, whilst taking into account the needs of other stakeholders. The successful implementation of the technology roadmap depends upon a number of complex interactions between commercial, political and technical aspects.

Although this roadmap is technically focused it also considers policy, environmental and commercialization aspects of the ocean energy sector, in order to display and put in context the influences of these externalities.

Keywords: Roadmap, Technology, International, Ocean

Hydrokinetic Energy in the United States – Resources, Challenges and Opportunities

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Session II (second half), Wednesday 14.50–15.55, Main hall

Renewable energy sources in the U.S. account for about 8.5 % of the electricity produced nationwide, 6.5 % of which comes from conventional hydropower plants. The total U.S. generation potential of emerging marine renewable energy sources, including wave, tidal, ocean currents and river hydrokinetic power, could provide a significant contribution to the U.S. renewable energy mix. This paper discusses the resource potential for power generation within different geographic regions and addresses current initiatives and barriers to development in the U.S.

Research by the Electric Power Research Institute (EPRI) suggests that the total recoverable resource is equal to about 10 % of the present U.S. electricity consumption. While these initial assessments provide a good first order indication of the resource potential, it is important to understand that many factors, such as electrical transmission capabilities, economic viability, environmental concerns and socio-economic considerations, impose additional limits onto these resources that may substantially alter the recoverable resources. Given the present technical, environmental and economic uncertainties, it is important to pursue all of these marine hydrokinetic resources in a sensible and strategic manner.

While the U.S. lags behind Europe in research, development and demonstration (RD&D) activities in the sectors of hydrokinetic energy conversion, interest in the U.S. is emerging: project developers, the states and the federal government are turning their attention to marine renewable technology. For example, the Department of Energy has begun active research in this area with an initial funding level for FY2008 of \$ 10 million, in addition to many state initiatives that are strategically pursuing these emerging generation resources.

Significant technical, economic, environmental and regulatory barriers remain to be addressed in order for this emerging industry to move forward with largescale commercial development. Experience with hydrokinetic energy conversion is thus far limited to a few prototype installations and provides a limited understanding of these issues. As such, it will be critical for the success of this industry to gain a full understanding of potential issues over a project life-cycle. Such understanding can only be gained in a sensible way from developer demonstration projects and early commercial adopters. Both market push (R&D) and market pull mechanisms (financial deployment incentives) will be required to successfully move this technology sector forward and develop the capabilities to sustainably tap into the enormous potential of ocean energy.

Keywords: United States, Resources, Programs, Policy

Economics of Future U.S. Wave Energy Markets: A Coupled Analysis of Regional Wave Climate and Energy Market Data

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Session II (second half), Wednesday 14.50–15.55, Main hall

This paper analyzes wave climate and energy market data to produce a regional picture of coastal U.S. wave energy market prices and wave power. Energy production capacity and mar-

ket cost per kWh trends are established to show prospective energy demand and earning capability for a wave power park in each coastal region. The state data is partitioned amongst the coastal regions: north or south Pacific coast, north or south Atlantic coast, and Gulf coast. Projected earnings data per coastal region is then coupled with the seasonal wave power available in those regions, with the introduction of 'prospective earnings per month per meter of wave-front'. The paper concludes with an economic comparison of power prices, usable wave power between coastal regions, and forecasted renewables demand.

Keywords: North American (U.S.) Wave Power, Wave Climate, Renewables Market, Price per Meter of Wavefront

Advances in Hawaii's Ocean Energy RD&D

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Session II (second half), Wednesday 14.50–15.55, Main hall

The wave energy resource in the Pacific Ocean surrounding Hawaii is abundant enough to, in theory, supply most of the state's electricity. In addition, the Hawaiian Islands are situated perfectly for Ocean Thermal Energy Conversion (OTEC). Tidal and ocean current resources, however, are less promising.

The State of Hawaii is proposing that an aggressive 40 % of its electricity come from renewable resources by the year 2030, a significant increase over the currently legislated 20 % by 2020 Renewable Portfolio Standard. Ocean energy is anticipated to play a role in achieving that goal. Recognizing that obtaining permits for renewable energy projects is a major barrier to their implementation, the state has hired a renewable energy facilitator to coordinate permits for large-scale projects. The Department of Business, Economic Development and Tourism has also been assigned the responsibility for designing a streamlined permitting process.

A number of ocean energy developers are pursuing RD&D projects in Hawaii. In 2008, a 2.7-MW project by Oceanlinx off the northern coast of Maui was announced. Later that year, OPT deployed its third PowerBuoy in Kaneohe Bay, an effort supported by the US Navy. A demonstration of CIIS/SG2's wind-wave buoy was also completed in Kaneohe Bay. Other wave energy companies have expressed interest in pursuing projects in Hawaii.

The University of Hawaii's Hawaii Natural Energy Institute (HNEI) has received one of two US Department of Energy awards establishing a National Marine Renewable Energy Center. HNEI anticipates implementing projects to test components, devices, and interconnection systems for wave energy at three sites on the islands of Oahu and Maui, and to pursue OTEC R&D at the existing Natural Energy Laboratory of Hawaii Authority (NELHA) facility on the island of Hawaii.

A 2008 agreement between Lockheed Martin Corporation and the Taiwan Industrial Technology Research Institute will support the development of a 10 megawatt pilot OTEC plant in Hawaii.

Keywords: Hawaii, OTEC, policy, research and development, wave energy

Topic 3

Wave and tidal energy resource characterization

Comparison of measured shallow-water wave spectra with theoretical spectra

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Session III-A, Tuesday 12.30–13.35, Gallery A

Usually there is little knowledge of long-term wave conditions at prospective sites for wave-power plants, while the deep-water or open sea conditions may be more known and geographically less varying. However, many wave-energy plants are intended for water depths small compared to the wave length. A concept for assessing design waves at a near-shore site is to transform the off-shore wave spectra to the target site by a model for spectral wave-energy transfer over the actual bottom topography. The inshore spectra can be used for linear statistics of extreme waves, design wave loads and for assessment of power take off. In this context it is important to know the realism of used spectral forms.

Based on 58 measured wave spectra at 6 m water depth at the near-shore wind farm Bockstigen in the Baltic the most realistic spectrum was found to be the TMA spectrum, which is a JONSWAP spectrum modified for shallow water. Some few examples are given. Normally wave-energy devices would be placed in somewhat deeper water and water depth correction will be smaller.

Keywords: Wave spectrum, measured shallow water waves, TMA spectrum

Assessing the Wave Energy Resource Using Remote Sensed Data

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Session III-A, Tuesday 12.30–13.35, Gallery A

The use of accurate remote sensed wave data in the coastal area (water depth up to 80 m) will enable a high quality characterization of the wave energy resource. Work has been carried out with this objective for a number of years namely assessing the quality of the radar altimeter and SAR sensors data.

In this paper a summary of the quality of wave period estimates from the NASA/CNES Jason radar altimeter is presented, showing that the analytical models that have been proposed in recent years provide already accurate results.

This paper also includes a verification of ESA ENVISAT SAR data (height, period and direction parameters in addition to the shape of frequency spectra) against NDBC buoy data, which has shown good accuracy for wave energy resource assessment. However, the long Exact-Repeat-Period of NASA (10 days) and of ESA satellites (35 days) poses serious limitation to the usefulness of their wave measurements except for long-term wave climate assessment. These shortcomings are expected to be overcome by the new high spatial-resolution TerraSAR-X satellite that is obtaining reliable data for nearshore areas, being able to provide data at 2–3 day interval.

Keywords: Remote Sensed (altimeter and SAR) Data, Period Algorithms, Directional Spectra

Determination of sea conditions for wave energy conversion by spectral analysis

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Session III-A, Tuesday 12.30–13.35, Gallery A

Conversion of wave motion to electrical energy depends on the instantaneous sea state at a given location, which can change on second, minute and hour timescales. In particular, information about wave groupiness (sets) is important in determining the efficiency of a wave energy converter at a given location. We report the use of a spectral method to analyze buoy time data to determine the sea state and express it as average wave height and period, as well as percentage slack time when the waves are smaller than the converter can use. The proposed method is a sinusoid estimation algorithm based on Capon's maximum likelihood estimate, which converges to the point spectrum of the sinusoids in the wave data. Therefore one can estimate sinusoid frequencies and amplitudes from a signal corrupted by noise. Present method is compared against FFT in frequency domain. The results of these spectral methods are used to obtain statistical characteristics of waves. As a golden standard, the same wave characteristics are also determined using a peak finding algorithm. The statistical wave data is then used to predict the power output of the wave energy converter using a model derived from experimental data. The implications for "harmonic" versus non-harmonic devices are discussed briefly.

Keywords: Non-stationary noise, spectral analysis, wave sets, wave statistics

Variability of Wind Sea and Swell Waves in the North Atlantic Based on ERA-40 Re-analysis

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Session III-A (second half), Tuesday 13.50–14.55, Gallery A

This study presents a qualitative assessment of the wave field in the North Atlantic (NA) basin, based on the ERA-40 wave re-analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). The wind sea and swell significant wave heights and mean wave lengths, seasonal and geographic distributions, are studied. The geographic distribution and dominance of wind sea and swell waves over the basin, in the winter and in the summer, are also studied. It

is shown that the wave field in the NA basin is mostly swell dominated, especially in the summer. The seasonality of the NA wave field is compared with the North Pacific. The qualitative characteristics of the wave fields in both basins is shown to be different. The centers of action of the wind sea and swell significant wave heights are identified using empirical orthogonal function (EOF) analysis.

Keywords: Wave climate, significant wave height, wind sea, swell, North Atlantic

Numerical Estimation of Incident Wave Parameters Based on the Air Pressure Measurements in Pico OWC Plant

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Session III-A (second half), Tuesday 13.50–14.55, Gallery A

The present study aims at assessing the key spectral parameters of the incident wave on a fixed oscillating water column (OWC) device, based on the air pressure measurements inside the chamber and on the numerical hydrodynamic coefficients of the device.

The methodology is based on the equation of continuity of the air in the time-domain and linear decomposition of the air flow in the usual terms of radiation and diffraction flows. By applying the Fast Fourier Transform, the time-domain equation is transposed to the respective frequency-domain equation.

This methodology was applied to the 400 kW OWC power plant, on the Island of Pico, Azores, which has been monitored since 2005 by the Wave Energy Centre. The numerical hydrodynamic coefficients obtained by the 3D radiation-diffraction boundary element code, AQUADYN-OWC, were used in this study.

No measurements of the incident wave in front of the plant are available; therefore the results obtained for a set of records are compared with forecast estimations for the site of Pico plant provided by INETI and also with the measurements of two directional wave rider buoys offshore Pico and Terceira islands. These data are provided by the Centre of Climate, Meteorology and Global Changes and propagated via the SWAN spectral wave model to the zone of interest.

Final objective is to improve the control of the Pico plant by assessing its performance for a range of sea states.

Keywords: Numerical Modelling, Pico OWC Plant, Wave Climate, radiation, diffraction, frequency domain

A new methodology to evaluate wave energy resources in intermediate depths. Application to the Asturias coast (North Spain)

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Session III-A (second half), Tuesday 13.50–14.55, Gallery A

In EWTEC2007 [1] a methodology was presented to evaluate the wave energy resource in coastal waters based on wave data obtained from numerical reanalysis of meteorological data. The proposed methodology had the following steps: (a) calibration of deep water wave reanalysis data; (b) sea states classification; (c) deep to shallow water propagation of the most representative sea states; (d) propagation of the complete series of sea states using an interpolation scheme; and (e) statistical characterization of the wave energy resources in the objective points.

In the new approach presented in this paper, some improvements to the different steps of the methodology have been incorporated. A maximum-dissimilarity algorithm has been applied to select a reduced number of sea states which are more appropriate for transferring the reanalysis database from deep water to shallow water.

Besides, wind energy generation has also been considered to improve the definition of local wave energy resources by incorporating wind data in the propagation of each sea state. Finally, a scattered data interpolation based on Radial Basic Function has been used to propagate the wave climate.

The proposed methodology has been calibrated and validated using satellite and buoy wave data for the wave resource analysis of the Asturias coast (North Spain). Some results of that analysis are finally presented.

Keywords: Wave energy resource, wave climate, wave propagation, classification algorithms

WorldWaves wave energy resource assessments from the deep ocean to the coast

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Session III-B, Wednesday 10.50–11.55, Gallery B

WorldWaves is a global wave and wind climate package developed through EU and industry sponsorship over many years. The offshore data incorporates global hindcast and operational wave and wind data from ECMWF, validated and calibrated with independent satellite and buoy data worldwide. These data, which may comprise full directional wave spectra time series, are used as boundary conditions to the latest version of the SWAN model for calculation of nearshore wave climate parameter and spectral time series and statistics. The WorldWaves methodology was originally developed in the late 1980s as part of a large wave energy resource mapping project being performed by OCEANOR at that time for SOPAC (South Pacific Geoscience Commission) in Fiji for many South Pacific island nations. Based on the WorldWaves global database, Fugro OCEANOR have created various high precision offshore wave energy resource and variability maps. In this paper some of the peculiarities of the global wave energy climate are discussed. Further, areas worldwide exhibiting a stable energy-rich wave climate are pinpointed as are areas with a favourable ratio of extreme to mean annual wave power density, a rough indicator of the economic potential of a site. Use of shallow water models such as SWAN together with short-term in-situ wave measurements (buoys) is generally needed at the feasibility stage for a proposed wave farm. At the pre-feasibility stage, the nearshore mapping of coastal wave energy resources is often required over larger areas (e.g., a country or state) and full SWAN modelling is usually too expensive. An alternative, utilising the offshore WorldWaves data together with nearshore satellite observations is a cost-effective alternative. This method is described and validated against nearshore buoy data on the US West Coast.

The package will also be demonstrated live at the conference exhibition to interested parties.

Keywords: WorldWaves, Wave Energy, Satellite Altimeter, SWAN

Development and preliminary assessment of an optical wave gauge

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Session III-B, Wednesday 10.50–11.55, Gallery B

A description and preliminary results are presented for a non-intrusive optical wave gauge based on the principle of optical triangulation. In the proposed implementation, a LASER source

beaming vertically downwards generates a spot of scattered light at the water surface. The spot is imaged by an off-axis video camera, and instantaneous wave height measurements are obtained by processing of the spot images. The spot position on the image is then transformed into a height value using a polynomial best-fit function established by an initial calibration. The gauge geometry is set to give a measurement range of 300 mm. The calibration method and apparatus are described. A detailed statistical analysis of the calibration results is presented both for the optical wave gauge and for a conductivity wave gauge used as a comparison. Dynamic measurements for regular waves of 25 mm and 50 mm amplitudes at 1 Hz are carried out with both probes. The resulting time series data are compared to a theoretical fifth order Stokes solution. While overall agreement is good for both types of probe, optical wave gauge data are found to provide a better fit to the theoretical solution, especially in the vicinity of wave crests.

Keywords: wave measurement, laser, optical, wave gauge

An atmosphere-wave coupled regional climate model

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Session III-B, Wednesday 10.50–11.55, Gallery B

A coupled regional atmosphere-wave model system is developed with the purpose of investigating the impact of climate changes on the wave field as well as feed-back effects of waves on the atmospheric parameters. This study focuses on the effects of introducing a two-way atmosphere-wave coupling on the atmosphere and on wave parameters. The model components used are the regional climate model RCA and the third generation wave model WAM. Introducing a two-way coupling results in an altered frequency distribution of wind speed and wave heights. When also the impact of swell is included there is a shift towards higher wind speeds as well as higher significant wave heights in the four investigated grid-points.

Keywords: wave-climate, coupled wave-atmosphere model, swell, atmospheric forcing

An assessment of tidal energy potential. The Lima estuary

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Session III-C, Wednesday 13.30–14.35, Gallery B

A hydrodynamic model was set up for the Lima estuary (Portugal) and a preliminary assessment of the strength of tidal currents to produce tidal energy was made. To calibrate the model results were compared with measured data, and the model tuned to reproduce water levels and currents in several locations within the estuary. The data was acquired with ADCPs, during a field campaign that was planned to cover a spring-neap tide cycle, in October 2006. The Advanced Circulation Model – ADCIRC was forced with the most important harmonic constituents present in the ocean tide signal. Upstream, in the river boundary, the discharge was taken from hydrographs. The wetting and drying tool was also applied and a detailed bathymetry was considered, since there are areas in the domain where salt marshes occur, drying out at low tide. The tidal currents potential were assessed for a scenario of tidal forcing only, without any river discharge. The lower estuary is occupied by the port infrastructure and navigation channels which conflicts with any kind of equipment installation. Values of the currents and water depths given by the model indicate that some places in the main channel of the middle estuary, might be interesting

to install micro turbines in the future, depending on the evolution of the requirements of this technology.

Keywords: Tidal current energy, hydrodynamic modelling, Lima estuary, ADCIRC model, wetting and drying

Tidal current turbine demonstration farm in Paimpol-Bréhat (Brittany): tidal characterisation and energy yield evaluation with Telemac

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Session III-C, Wednesday 13.30–14.35, Gallery B

On the 15th of July 2008, EDF announced its decision to build the first tidal turbine demonstration farm in France to produce electricity from the energy of tidal currents. Between 2011 and 2012, a few turbines representing several MW will be installed and connected to the grid off Paimpol-Bréhat (Brittany).

EDF R&D has been developing the Telemac-2D software. Over the past twenty years, that allows to model and simulate river and coastal hydrodynamic phenomena. At the Paimpol-Bréhat site, it is used to calculate tidal current characteristics and to assess the tidal energy yield potential produced by turbines exploiting such currents.

The zone where the farm is to be built is characterised with respect to tidal current potential. Data comes from a numerical Telemac-2D model of the Paimpol-Bréhat zone and current measurements from ADCP deployed at sea in 2005 and 2008. The use of realistic data taken from a site appears to be among the crucial technical parameters for site selection and the optimal positioning of the devices within the array.

Different methodologies for tidal resource assessment are described and compared. In particular, the respective strengths and weaknesses of some farm methods used in the Paimpol-Bréhat site study are discussed on the basis of a theoretical nine-turbine farm.

Keywords: Tidal currents, numerical modelling, at-sea measurements, resource assessment

A Three-dimensional Hydrodynamic Model of Inland Marine Waters of Washington State, United States, for Tidal Resource and Environmental Impact Assessment

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Session III-C, Wednesday 13.30–14.35, Gallery B

Inland coastal waters of the State of Washington, United States, are fjord-like in character and feature many passages where substantial tidal currents with speeds up to three meters per second or greater occur. Combined with close proximity to the major metropolitan area of Seattle and easy access to the power grid, the region is a prime candidate within the United States where tidal power generation can play a significant part in the energy portfolio. The Northwest National Marine Renewable Energy Center is developing a three-dimensional model of tidal and subtidal circulation of these waters. The model is based on Stanford University's SUNTANS code, is non-hydrostatic, and allows wetting and drying of tidal flats. It covers the eastern Strait of Juan de Fuca, Puget Sound, San Juan and Channel Islands, and the southern Georgia Basin with an unstructured triangular mesh of 250 m average resolution. The model is forced with adjusted tidal currents from WebTide along open boundaries in the Straits of Georgia and Juan de Fuca. In this paper the barotropic tidal response of the model is reported. The

model is calibrated against compiled tidal data for the region. Tidal currents in the channels are characterized in terms of velocity and energy density, and the system response is characterized in terms of the sea surface height variability. Future plans for the model include incorporation of baroclinic processes and representation of in-stream energy conversion arrays, assessment of the impact of the arrays on barotropic and internal tides, and of mixing and flushing of waters in the basins.

Keywords: fjord estuary, numerical modelling, tidal resource assessment

Correcting the Under-estimate of the Tidal-Stream Resource of the Pentland Firth

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Session III-C (second half), Wednesday 14.50–15.55, Gallery B

The equation used for predicting the output of a wind turbine in an open flow field uses the cube of wind velocity. But the correct equation for an hydraulic machine in a closed duct uses the first power of flow rate times the pressure head. This paper argues that the second equation should be used for close-packed tidal-stream turbines in long channels where the water has no easy escape path and that it will lead to a much larger estimate for the size of the resource. It seems wrong to base the design of tidal steam plant on a fundamental misunderstanding of the energy source.

Keywords: Pentland Firth, tidal-stream energy, bed friction, vertical-axis turbine, variable-pitch, flow impedance

High-resolution metocean modelling at EMEC's (UK) marine energy test sites

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Session III-C (second half), Wednesday 14.50–15.55, Gallery B

To support and improve the evaluation of the test results of wave energy and tidal energy generators, it is important to understand the detailed physical conditions at the test sites. EMEC has chosen DHI's MIKE modelling technologies for studying water levels, currents and waves at their test sites. DHI has assisted EMEC in constructing numerical hydrodynamic and wave models of the Orkney Islands using the flexible mesh version of MIKE 21. This model permits spatial varying resolution, so that the complex tidal channels and local topographic features that may influence the tidal and wave dynamics can be sufficiently resolved. This paper highlights the modelling activities for EMEC's two test sites.

Keywords: EMEC, Orkney, test sites, tidal, metocean, wave-current interaction, numerical modelling, MIKE by DHI

Wave and Tidal Power measurement using HF radar

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Session III-C (second half), Wednesday 14.50–15.55, Gallery B

HF radar measurements are presented focussing in particular on the estimation of both wave and

tidal power to demonstrate that HF radar has a role to play in both measuring the resource and providing monitoring data during power extraction, device installation, testing and operations.

Keywords: HF radar, wave power, tidal power, buoy

Analysis and Comparison of Tidal Datasets

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

Tidal resources are highly variable, spatially and temporally. For tidal current energy to be economically exploited, certain conditions need to be fulfilled. Principally the strength of the resource needs to be quantified before it can be effectively utilised. This paper will build on and expand the simplified tidal analysis methods adopted in [1] and other simplified regional and national scale resource assessments. High quality data collection for interesting sites is highly desirable but expensive, difficult to extrapolate over a larger area, and hence unsuitable for national scale resource analysis. Existing publicly available datasets have so far typically been used to examine the resource. A methodology to combine all of the available datasets to produce an improved resource assessment methodology is desirable.

Combining datasets will only be suitable if there is good correlation and consistency between them. The suitability of combining three UK wide datasets will be examined in this analysis. The data sources considered are:

- UK Moored Current Meter Data,
- UK Hydrographic Office publications, and the
- DTI Atlas of UK Marine Renewable Energy Resource.

The datasets do not generally coincide spatially or temporally. Analysis to enable direct comparison of these datasets for a case study region will be presented. This will inform whether the methodology of analysis and combining of datasets has potential for application at larger scales. If with additional processing, datasets can be combined, considerable improvement will potentially be realised in analysing the UK tidal energy resource. Future work is intended to combine outputs from this research with similar datasets for other intermittent renewable resources in order to examine their combined output and their potential integration into the existing electrical network infrastructure.

Keywords: Resource assessment, Tidal analysis, Harmonic tidal analysis, model skill

Spatial & Spectral Variation of Seaways

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The wave energy industry is entering a new phase of precommercial and commercial deployments of full-scale devices, so better understanding of seaway variability is critical to the successful operation of devices. The response of Wave Energy Converters (WEC) to incident waves govern their operational performance and for many devices, this is highly dependant on spectral shape due to their resonant properties. Resource assessments, device performance predictions and monitoring of operational devices will often be based on summary statistics and assume a standard spectral shape such as Pierson-Moskowitz or JONSWAP. Furthermore, these are typically derived from the closest available wave data, frequently separated from the site on scales in the order of 1 km. Therefore, variability of seaways from standard spectral shapes and spatial

inconsistency between the measurement point and the device site will cause inaccuracies in the performance assessment. Potential differences in estimated and actual incident wave power are investigated using measured data. Concurrent wave data from two wavebuoys have been collected from the EMEC full scale test facility in Orkney, Scotland and the Galway Bay benign test site, Ireland along with single buoy data from the Wave Hub site off the north Cornwall coast in the UK.

Spatial variability is investigated through the examination of limited data from wave measurements taken at separations of 200 m, 500 m and 1500 m. Differences between concurrent measurements are identified and compared to theoretically predicted variability, in terms of their magnitude and statistical properties. Comparisons of the data over the available separations indicate a possible dependence of the measured differences in the spatial domain, although site-specific properties must also be considered.

The deviation of the measured data from the empirically derived spectral shapes is investigated, quantified and compared to other sites from published data. This investigation involves the identification of bi-modal seaways and it is found that this deviation reduces with increasing wave height, although the degree of deviation, which is being investigated here, is site specific to some degree.

Finally, this analysis is implemented for chosen elements of the wave height-period scatter diagram that are populated at the selected sites. The analysis techniques derived are employed to quantify not only spatial and spectral variation and variability, but also variations from benign site to fullscale site. The analysis highlights potential variations in power incident at a site from those estimated using a standard spectral shape at a separate measurement point.

The results of the work presented here are only indicative as the spectral variation work is based on just four months of data, while the spatial variation exercise is applied to just 1 month's concurrent measurements. Robust conclusions can only be drawn when the methods are applied to a more extensive database.

Keywords: wave energy, wave spectra, bootstrap analysis

Wave energy resource off the French coasts: the ANEMOC database applied to the energy yield evaluation of Wave Energy Converters

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

A numerical wave database called ANEMOC has been built by EDF R&D LNHE by hindcasting wave conditions over a period of 23 years and 8 months, between 1979 and 2002. The simulations of wave conditions are carried out with the third-generation spectral wave modelling software TOMAWAC and are driven by wind fields from the ERA-40 meteorological reanalysis produced by the European Centre for Medium-range Weather Forecast. Two nested models, an oceanic one and a coastal one, which zooms on the French coasts of Atlantic Ocean, English Channel and North Sea, have been implemented. The results have been validated with buoy data over a period of two years, and can be used to determine medium wave conditions as well as statistically extrapolated extreme wave heights.

After a description of the main characteristics of the database, the paper focuses on the application of such a database for evaluating the wave energy resource and the wave energy yield of Wave Energy Converter (WEC) technologies in Europe, and in particular off the French coasts.

Keywords: Wave atlas, wave energy resource, WEC energy yield, third generation spectral wave model

Assessment of Wave Energy around Italy

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

A preliminary assessment of the available wave energy around Italy is presented. The computations have been conducted by using the wave data collected since 1989 by the Italian Wave Network. The yearly mean power is maximum at the Alghero wave buoy located on the West of Sardinia Island and it reaches 13.1 kW/m.

Keywords: Wave Energy, Italian Seas, Wave Data, Wave Energy Atlas, Wave Power

Topic 4

Device development and testing

A Parametric Experimental Study of the 2D Performance of a Ducted Wave Energy Converter

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Session IV-A, Tuesday 13.50–14.55, Gallery B

Offshore Wave Energy Limited's "OWEL" wave energy converter is a novel design that uses the forward surging motion of deep water waves to capture and compress air. Uni-directional compressed air flow is used by the device to drive a turbine and generator to produce electricity. Previous experimental studies provided useful initial information about the general operating principles and basic trends in device performance. This paper serves as a progress update of the small scale, 2D experimental work being carried out at the University of Southampton. Testing has investigated the relationships between device performance and wave characteristics as well as trialling a series of different geometric configurations of the model.

Keywords: Wave Energy, OWEL, Experimental, Small Scale Model

Performance optimisation of a modified Duck through optimal mass distribution

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Session IV-A, Tuesday 13.50–14.55, Gallery B

A new design for the solo desalination Duck Wave Energy Converter is being studied at the University of Edinburgh. The key innovation is the modification of the profile. A numerical hydrodynamic model showed that similar performance could be obtained by using a circular cylinder with an off-centred axis of rotation. The principle advantage of this new design is the reduction of the cost of the manufacturing process. A 1:33 scale model was built to validate the numerical predictions and has been tested in a wave tank in regular and irregular seas.

The optimisation of the performance of this device requires a systematic investigation of the effect of several variables. In this paper the effect of mass redistribution is analysed. A simplified one degree-of-freedom frequency-domain model with its power-take-off based on linear damping is used and an equation for the position of the ballast mass that maximises the performance of the device for a certain wave exciting frequency is derived.

It is shown that by relocating the ballast (i.e. changing the inertia of the Duck) a new condition that optimises the performance of the device for a particular wave climate is obtained.

Keywords: Wave Energy Converters, Edinburgh Duck, WAMIT, optimisation of performance, mass distribution, vapour compression desalination

Development of advanced wave power generation system by applying gyroscopic moment

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Session IV-A, Tuesday 13.50–14.55, Gallery B

Authors have been developing a pure mechanical wave power generation system. The principle of the system is the application of the gyroscopic moment produced by the rotation of large flywheels and the swing of a float excited by wave motion. This paper presents the principle of the system, the developing process of prototype systems and their test results. It was confirmed that the system has higher efficiency than conventional OWC wave power generation systems and sufficient reliability for actual application. The system will be applicable for distributed electric source for small island and ports.

Keywords: Wave power generator, Renewable energy, Gyroscopic moment

In field measurements on a small scale OWC device

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Session IV-A (second half), Tuesday 15.10–16.15, Gallery B

A 1:10 scale model of an ocean OWC breakwater was realised and put at the sea off the beach of Reggio Calabria (Italy). The breakwater (about 16 m long and 3.5 m height) was placed on a 2.1 m bottom depth, and embodied the REWEC wave energy converter (Boccotti *et al.*, 2007, J. of Ocean Engineering, 34, 820–841). A small scale Wells turbine was installed onto the central caisson of the breakwater. Two different experiments were carried out. The first one aimed to test the energy absorption capabilities of the system and to analyse the waves-absorber interaction mechanism. The second experiment aimed to test the Wells turbine under oscillating randomly varying flows produced into the plant by sea waves. The goals of these experiments involved some measurements made critical because of the harsh environment, the high variability of randomly oscillating flows and unavoidable scale effects. Here, we show how these measurement difficulties were overcome by developing "ad hoc" measurements techniques. In particular, in this paper some critical measurements are described: the measurement of the water discharge through the plant, necessary to estimate the absorbed power; the instantaneous value of the torque exerted by the air flow on the turbine, necessary to analyse the actual unsteady behaviour of the turbine. Both measurements were carried out by using two different techniques, in order to make them robust.

Water discharge were calculated by integrating the acceleration of the water column, by recording the pressure simultaneously in different point along the streamline. This punctual measurement was compared with measurements carried out by an ultrasonic probe located on the roof of the plenum chamber. Because of the width of the sound beam, this measurement is space averaged.

Torque measurements were carried out by using the DC motor coupled with the Wells turbine as an electromechanical transducer. The procedure proved to be accurate once calibrated.

A not trivial task was to separate, in the unsteady randomly varying reverse flow, the share of power transferred to the blade by the air current, from the shaft power driving the turbine, being necessary to sustain the rotation of the wheel many times in the cycle, because of high incidence of friction power losses in the small scale model.

Keywords: OWC, Wells turbine, unsteady performance, hysteresis

Statistical analysis of power production from OWC type wave energy converters

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Session IV-A (second half), Tuesday 15.10–16.15, Gallery B

Oscillating Water Column based wave energy plants built so far have experienced a low efficiency in the conversion of the bidirectional oscillating flow. A new concept is considered here, the LeanCon Wave Energy Converter (WEC), that unifies the flow direction by use of non-return valves, into a unidirectional flow, making the use of more efficient air turbines possible. Hereby, a more steady flow is also obtained.

The general objective of this note is to examine, the power take off (PTO) efficiency under irregular wave conditions, for WECs with flow redirection. Final practical aim is to identify a method that allows the choice of the optimal power generation capacity for which the device should be designed, when subjected to any given wave climate.

The analysis is based on the experimental results of existing tests carried out in the 3D deep water wave tank at Aalborg University, Denmark.

First, the power measured at the modelled PTO is compared with the available incident wave power in order to examine the overall system response in a scaleindependent manner. Then, the power production density function is fitted to a simplified shape, whose parameters are related to the tested sea state conditions (wave period, wave height). Average performance and stochastic variability is thus obtained for any sea state and therefore also for the annual wave climate of interest.

An example application of a LeanCon unit is carried out for a location off-shore Cagliari (Italy).

Conclusions provide economic criteria for estimating the optimal value of power for which the PTO should be designed.

Keywords: power production, oscillating water column, statistic distribution

Practical design and investigation of the breakwater OWC facility in China

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Session IV-A (second half), Tuesday 15.10–16.15, Gallery B

The breakwaters are utilized for absorbing wave energy to provide suitable berthing conditions for the harbors. The caisson breakwater can be modified as the air chamber of the Oscillating Water Column (OWC) Wave Energy Conversion (WEC) facilities. In the present paper, the integrated structure of Caisson breakwater-OWC chamber is practically designed. The experiments are performed in the wave flume to obtain the oscillating amplitude of inner water

column inside the chamber, which are usually employed to demonstrate the operating performance of the OWC chamber. A numerical wave tank based on the two-phase VOF model is established to generate 3D incident waves. The numerical wave tank consists of the continuity equation, Reynolds-averaged Navier-Stokes equations and two-phase VOF volume fraction equations. The standard k- ϵ turbulence model, finite volume method, NITA-PISO algorithm and dynamic mesh technique are employed. The numerical results are compared and validated by the above corresponding experimental data. The effects of several incident wave conditions and shape parameters on the wave energy converting efficiency and performance of integrated system are investigated.

Keywords: Caisson breakwater, wave energy, OWC, physical experiments, numerical simulation

Modification of power characteristics in an array of floating wave energy devices

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Session IV-B, Wednesday 8.10–9.15, Main hall

In this paper we seek configurations of wave energy devices that help to achieve certain objectives, such as maximising power for a given sea state. Preliminary results from a genetic algorithm optimisation and a new heuristic array construction method are presented. These procedures employ an exact hydrodynamic interaction technique, which is used to assess the performance of the resulting arrays. The power enhancing effect of the arrangement ($\bar{q}$ -factor) is presented for regular incident waves with a range of frequencies and directions. Finally we evaluate how effective the two optimisation approaches are in achieving the desired modifications to the collective behaviour of devices.

Keywords: Array, Linear wave theory, Genetic algorithm

Mutriku Wave Power Plant: from the thinking out to the reality

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Session IV-B, Wednesday 8.10–9.15, Main hall

From the very first conception of the wave power plant at Mutriku through to its completion, this article shares the process of maturing and crystallising an entirely new project. Not only was this the first multiturbine facility to be installed in a breakwater, it was also the world's first commercial project: in other words, a project in which a technology firm sold a power-generating facility to an investor for commercial operation. As well as addressing other issues, the article focuses on the unusual nature of the building process involved in the civil engineering.

Keywords: Breakwater, Mutriku, onshore, OWC, wave energy

A Pilot Study Into the Optimization of the Shape of a Wave Energy Collector by Genetic Algorithm

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Session IV-B, Wednesday 8.10–9.15, Main hall

This pilot study forms part of research into the optimization of the shape of a wave energy

collector to improve energy extraction using genetic algorithms. Two main types of genetic algorithms exist, differentiated by the use of binary or real numbers as object descriptors. The study is intended to ascertain if one type is more suited to the specific problem by comparing the performance of two example algorithms. The algorithms optimize the shape of a bisymmetric wave energy collector moving in two degrees of freedom (surge and pitch). The collector is described by ruled surfaces in one quadrant, defined by the positions of seven vertices. The cost function is based upon a first-order model of the system, with the collector optimally tuned to a number of incident regular waves with a generalized occurrence distribution. High velocities and large collector volumes are penalized. An assessment of the performance of the two algorithms is made, looking at the improvement in value and change in diversity of the respective populations. A comparison is also made of the computational requirements of the different parts of the optimization process.

Keywords: Genetic algorithms, marine energy conversion, optimization methods, WEC design

Development of Marine Renewable Energy in the South West of England: The Wave Hub and PRIMaRE

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Session IV-B (second half), Wednesday 9.30–10.35, Main hall

The UK Government has committed to cut the UK's emissions of carbon dioxide by 20 % below 1990 levels by 2010 and to increase the amount of electricity produced by renewable energy sources to 10 % by 2010 and 15 % by 2015. Wave and tidal energy are recognised as key renewable energy technologies for the UK, and the South West region in particular has the potential to generate substantial amounts of renewable energy from its wave and tidal stream resources. In recognition of the potential for the industry in the region, the South West of England Regional Development Agency (SWRDA) is supporting demonstration projects in marine energy through the Wave Hub project and PRIMaRE, the Peninsular Research Institute in Marine Renewable Energy.

Keywords: Marine renewable energy, Wave Hub, Wave energy array demonstration project

Foundation load analysis of Oyster using a five degree of freedom load transducer

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Session IV-B (second half), Wednesday 9.30–10.35, Main hall

The Oyster Oscillating Wave Surge Converter is a seabed mounted wave energy device that consists of a buoyant flap that is free to oscillate about a pivot. It completely penetrates the water column and is located within the near shore region in a water depth of 13 m.

As with any marine wave energy converter the foundation design and the survivability characteristics of the device itself are of paramount importance.

To address this issue an extensive series of experiments was carried out to investigate the foundation loads experienced by the device in extreme sea conditions. Experiments were conducted using a scale model of Oyster and the resultant foundation loads were measured using a five degree of freedom load transducer developed specifically for this purpose.

This paper will discuss the design, calibration and operation of the five degree of freedom load transducer as a well as a discussion on error checking procedures used to verify the accuracy and resolution of the device.

Samples of the data generated during the test series are presented to demonstrate the operation of the load transducer. A discussion of Extreme Value Analysis (EVA) data processing techniques used to estimate the loading upon the flap for a range of events with increasing return periods is also presented.

Keywords: extreme loading, extreme value analysis, load transducer design and operation, tank testing

Current and Future Developments of the C-GEN Lightweight Direct Drive Generator for Wave & Tidal Energy

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Session IV-B (second half), Wednesday 9.30–10.35, Main hall

The C-GEN is a novel permanent magnet generator aimed at reducing overall system mass in direct drive power takeoff applications. The design of a C-GEN generator requires the combination of electromagnetic, structural and thermal models. Two rotary prototypes of 15 & 20 kW have been constructed and tested and the 15 kW prototype has been fitted to a wind turbine. A 1 kW linear generator has been tested and is being modified for flooded operation meanwhile a larger 50 kW prototype is being designed. A feasibility study of C-GEN technology in four different wave and tidal projects is being undertaken.

Keywords: Direct Drive, Linear Generator, Power Takeoff

Experimental Testing of the Transverse Horizontal Axis Water Turbine

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Session IV-C, Wednesday 8.10–9.15, Gallery A

This paper outlines the procedures and preliminary results for a set of experiments on the Transverse Horizontal Axis Water Turbine (THAWT), which is a variant of a Darrieus turbine. Testing of a 1/20th scale device was conducted in the combined wind, wave and current tank at Newcastle University. Flow depth and velocity were varied over a range of realistic Froude numbers for tidal streams. Various configurations of the device were tested to assess the merits of the THAWT design. Variants included a parallel bladed device, a “truss” device and a parallel bladed device configured with blades pitched relative to the pitch circle tangent. Experiments were carried out using a speed controlled motor, allowing quasi-steady results to be taken over a range of tip speed ratios. Preliminary results demonstrate that, over a range of flow conditions, the device is capable of exceeding the Lanchester-Betz limit for kinetic efficiency. This is principally due to the relatively high blockage ratio which can be achieved with such a device.

Keywords: Darrieus, Horizontal axis, THAWT, Tidal stream

Contra-rotating Marine Current Turbines: Single Point Tethered Floating System – Stability and Performance

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Session IV-C, Wednesday 8.10–9.15, Gallery A

The Energy Systems Research Unit within the Department of Mechanical Engineering at the University of Strathclyde has developed a novel contrarotating tidal turbine (CoRMaT). A series

of tank and sea tests have led to the development and deployment of a small stand-alone next generation tidal turbine. Novel aspects of this turbine include its single point compliant mooring system, direct drive open to sea permanent magnet generator, and two contra-rotating sets of rotor blades.

The sea testing of the turbine off the west coast of Scotland in the Sound of Islay is described; the resulting stability of a single-point tethered device and power quality from the direct drive generator is reported and evaluated. It is noted that reasonably good moored turbine stability within a real tidal stream can be achieved with careful design; however even quite small instabilities have an effect on the output electrical power quality. Finally, the power take-off and delivery options for a 250 kW production prototype are described and assessed.

Keywords: contra-rotating, stability, tidal, turbine

Design of a Gravity Stabilised Fixed Pitch Tidal Turbine of 400 kW

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Session IV-C, Wednesday 8.10–9.15, Gallery A

This paper describes the design of a fixed pitch horizontal axis tidal turbine for use in a DeltaStream device. The DeltaStream unit consists of three turbines each mounted on a swivelling nacelle atop a pylon which is located at the vertex of a delta shaped freestanding structure. The tidal turbine has to be designed so that the total thrust on the assembly is less than the frictional forces opposing any motion. This leads to a design requirement where the power-thrust ratio is a maximum for the turbine. This is especially difficult with a fixed pitch turbine where it is required to maximise the power over the tidal cycles for a maximum possible thrust. The turbine blades were designed using design methods more commonly used in turbomachinery rather than the Blade Element Method (BEM) used in wind turbines. The design was then assessed by CFD using CFX over a range of tip speed ratios to generate a set of non-dimensional characteristics which could be used, together with a tidal probability distribution from EMEC, to generate average powers and peak loads. The unsteady loads were assessed by estimating the level of the mean unsteady velocity and how the rotor would respond in a one-dimensional manner. Site specific data could then be applied to obtain more realistic loads.

Keywords: Fixed pitch, Freestanding, Tidal turbine

Analysis of wave reflection from wave energy converters installed as breakwaters in harbour

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Session IV-D, Thursday 9.00–10.05, Gallery B

Amplification and renovation of harbours, none the last for the need of straitening existing structures because of the increased storminess due to climate change, is a practice that is repeating itself all around the world.

To this purpose, integration of breakwaters and Wave Energy Converters (WECs) based on two different technologies, one based on the overtopping principle and the other of Oscillating Water Column (OWC) type, revealed to be suitable with different advantages compared to off-shore installations, among the others: sharing of costs, cheaper accessibility and maintenance, lower loads on the structure, i.e. better survivability.

Nevertheless these devices must comply with the requirements of harbour protection structures and thus cope with problems due to reflection of incoming waves, i.e. dangerous sea states close to harbours entrances and intensified sediment scour, which can lead to structure destabilization.

The present paper aims to analyse wave reflection from OWC and Sea Slot-cone Generator (SSG) converters, based on experimental results obtained in 2D and 3D facilities.

The applicability of formulae available in the literature and derived from coastal structures experience are checked.

Consideration on induced scour and structure stability are also carried out, and solution for design improvements are finally drawn.

Keywords: wave reflection, sea slot cone generator, oscillating water column, scour, experiments, formulae

Resonating wave energy converter for delivery of water for desalination and energy generation

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Session IV-D, Thursday 9.00–10.05, Gallery B

The supply of clean drinking water is of great concern in many remote coastal areas. One method of providing this clean water is the process of desalination of seawater. This process generally requires either high temperatures (evaporation processes) or very high pressures (6 MPa for reverse osmosis processes).

Current research at the University of Southampton focuses on the development of a wave powered standalone system for desalination and/or electricity production. A high pressure pump has been developed for pressurization of seawater for direct use in a reverse osmosis desalination process. The high pressure pump is driven by a supply of water, of 2 meter head, delivered by a simple wave energy converter. The proposed system has the benefit of simple technology and possesses significant potential for use in developing countries. This paper focuses on the device which will deliver water to the high pressure pump. The delivery device constitutes a wave energy converter and uses the principles common to most Oscillating Water Column (OWC) systems to pump water.

Keywords: OWC, desalination, energy conversion

Experimental investigation of power capture from pitching point absorbers

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Session IV-D, Thursday 9.00–10.05, Gallery B

This paper presents results from an experimental study on the power capture of bottom-pivoted pitching point absorbers in intermediate water depth subjected to regular and irregular waves. The present research investigates the respective influence of parameters such as geometry, damping and inertia modification (ballasting) on the performance of bottom-pivoted pitching wave energy converters in realistic sea states. Results indicate that this type of wave energy device performs best in moderate sea states, although the net power output would be greater in larger sea states. The pitch displacement angle, relative to vertical, is typically less than $\pm 15^\circ$ under normal operation. The two most influential parameters, damping and ballasting,

have a dramatic influence on the performance of the device. Moreover, it is shown that these parameters can be adjusted in response to the wave conditions to optimise power capture. From the results of the experiments in irregular waves, a full scale cylinder-shaped prototype of 6 m diameter located in 25 m water depth could absorb approximately 130 kW (average) in nominal winter conditions (based on observations from the North Atlantic) and approximately 40 kW (average) in summer sea states.

Keywords: Experimental, Pitch, Point-absorbers, Wave Energy

Development of a multi-bladed 250 kW pitching wave-energy converter

C. A. Gonzales, G. Kloos, T. Finnigan

BioPower Systems Pty. Ltd., Australia

Session IV-D (second half), Thursday 10.20–11.25, Gallery B

This paper outlines the methodology to develop a multi-bladed 250 kW pitching wave-energy converter based on the swaying motion of sea plants in the presence of ocean waves.

The studies presented here focused on model-tank tests together with dynamics (time-dependent) simulations. These tank tests focused on adjusting and optimizing control variables and the geometric design of the device to allow for the achievement of a required power. The main variables considered here were the blade spacing, ballasting, and power capture. Time dependent simulations based on a theoretical model of the system, once validated with the tank tests at different sea-states, ballasts and blade spacings, provided the power output at different wave conditions.

Keywords: Ballasting, spacing, multi-bladed, pitching wave-energy converter, wave power

Wavebob – Research & Development Network and Tools in the Context of Systems Engineering

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Session IV-D (second half), Thursday 10.20–11.25, Gallery B

Following a sequential development path with growing model size Wavebob has in recent years gained valuable experience during large scale sea trials. For the important advancement from sea going models to full scale demonstration of pre-commercial prototypes a transition in the development process is required.

The implemented systems engineering approach enables Wavebob to effectively work within a powerful research & development network, efficiently employ a range of development tools and progress a number of parallel development threads. This paper described the concept of systems engineering in its application to wave energy converters (WEC), highlights its effectiveness in mitigating risk and accelerating the development process towards full scale demonstration of commercial operations.

Keywords: Research & development network, systems engineering, wave energy converter development

The Ocean Harvester – Modelling, Simulation and Experimental Validation

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Session IV-D (second half), Thursday 10.20–11.25, Gallery B

Among the significant difficulties of developing commercially viable wave power has been survivability in storm conditions and achieving high capacity factors. The oscillating wave motion, constantly changing wave-size, and extreme energy levels during storm conditions often lead to difficulties in reaching high capacity factors, keeping the system complexity down and avoiding over dimensioning.

The Ocean Harvester is based on an innovation addressing these issues. What is unique with this concept is the way a counterweight is used to achieve a limited load on the generator and thereby a levelled power output that can be controlled to match the average level of incoming wave energy. These characteristics enable an exceptionally high capacity factor, excellent survivability and low system complexity, which altogether may lead to low capital- and O&M costs.

This paper presents the working principle of the novel concept and introductory coordinated theoretical and experimental investigations of performance characteristics. Theoretical and experimental results agree very well and further simulations with the verified model using real wave data clearly show the advantage of the proposed concept. A high capacity factor is proven and the design obviously only requires existing types of components, making cost-efficient wave energy conversion feasible.

Keywords: Ocean Harvester, ocean wave energy, mechanical transmission system, landbased testrig

The bioSTREAM tidal current energy converter

G. Kloos, C. A. Gonzales, T. D. Finnigan

BioPower Systems Pty. Ltd., Australia

Session XII (poster session), Tuesday 16.30–18.30, Main hall

Renewable energy technologies are being developed to address increasing electrical energy needs, to help reducing the usage of fossil fuels for energy generation and at the same time decrease the dependency on fossil fuels.

This paper presents the bioSTREAMTM tidal stream power generation technology, currently being developed by BioPower Systems Pty Ltd. A prototype device is soon to be built and installed in a tidal stream off Flinders Island, Australia. The device is based on the oscillating hydrofoil principle. The relative motion of the tidal current over the foil section of a hydrofoil induces hydrodynamic lift and drag forces. These forces are due to a pressure difference on the hydrofoil. The tangential component of these forces with respect to a pivoting arm is used to drive hydraulic rams in a reciprocating fashion and to pump high-pressure hydraulic fluid, which is in turn used to drive a variable displacement hydraulic motor coupled to an electrical generator.

This paper describes the tidal stream energy conversion technology and the engineering and design of a full scale prototype device with a rated capacity of 250 kW, followed by the development of time-dependent dynamic simulations and the use of CFD simulations and scale model testing to obtain important device variables and characteristics. The principles of operation, the degree of complexity in optimising the device, and the underlying mathematical model are also introduced and explained. The choice of composite materials in the design led to a strong and lightweight design, which is an important aspect for an oscillating hydrofoil.

A future outlook of the technology is presented, where scaling-up from the prototype capacity to megawatt capacity and farm installations of the devices become important factors.

Keywords: Oscillating hydrofoil, Renewable energy, Tidal energy

Considerations of Improved Tidal Stream Turbine Performance Using Double Rows of Contra-Rotating Blades

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This paper describes work involved with modelling, using the CFD package FLUENT, a contra-rotating double row set of 3 bladed tidal turbines. The design of these turbines is to assess the potential increase in the power, torque and axial thrust generated over a conventional single row propeller.

A single row 3 bladed horizontal axis tidal turbine (HATT) has been created and validated with data from a 0.5 m diameter laboratory scale turbine. This data has then been scaled up to 10 m diameter turbines. A series of models have been produced at the 10 m diameter scale which incorporates 2 rows of blades. The spacing between each row of blades has been increased to establish the wake characteristics and the turbine characteristics, in particular for power, torque and axial thrust for each design scenario. Each model is compared against the single row turbine. The row spacing has been non-dimensionalised to the turbine hub diameter to provide a more pragmatic approach to the spacing selection.

The results from the CFD models show that there is a negligible increase in the power generated but an increase in the axial load on the turbine. The nett torque acting on the device is, however, considerably reduced, and potentially negated, so potentially helping the turbine to align to the tidal flow.

Keywords: CFD, Contra-rotating blades, power, torque

Design and Construction of an Experimental Wave Energy Device Emulator Test Rig

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

An experimental test rig has been constructed which is capable of recreating within a laboratory setting the dynamic response exhibited by a prime mover onto a motor-generator assembly. The prime mover can simulate from real or modeled time series data any varying source such as a wind turbine, a hydraulic motor or a wave energy air turbine.

The initial application around which the test rig has been designed is a wave energy converter. In this regard, the case study considered in this paper is the emulation of a floating Oscillating Water Column-Wells turbine device operating under a number of sea states. Particular attention has been given to the control algorithm of such a converter and to the effect on device performance including the flywheel storage. Simulations were conducted in Matlab/Simulink and results demonstrate by means of peak to average power ratios that significant improvements in the system's performance were achieved for any given sea state with the addition of a flywheel energy storage device. In particular, the ratios for power exported to the grid were seen to improve by up to a factor of 4.5.

Keywords: Flywheel energy storage, Induction generator, Oscillating water column, Wave energy device, Wells turbine

Prototype test and modeling of a combined wave and wind energy conversion system

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This paper deals with the possibility of mounting wind turbines on a wave energy plant. The basis is the Poseidon combined wave and wind energy conversion platform. The wave energy part of the Poseidon platform has been tested at sea and a comprehensive measurement campaign has been carried out, measuring platform motion and waves, current and wind conditions. The measurement form the basis for aeroelastic simulations of a wind turbine mounted on the platform. The aeroelastic simulations show that the tower bottom bending moment has increased and extra considerations need to be taken about the turbine tower construction. The specific turbine is found to damp the platform roll motion.

Keywords: wave energy, wind energy, multipurpose platform, Poseidon

OCEANTEC: Sea Trials of a Quarter Scale Prototype

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

Although the first attempts to exploit wave energy go back to similar periods of other renewable energy sources, no particular technology has yet proved to be successful. Survivability in the ocean harsh environment will be one of the key features for commercial success of Offshore Wave Energy Converters.

This paper describes the sea trials results of a new offshore Wave Energy Converter, namely the OCEANTEC WEC. The OCEANTEC WEC is an offshore floating structure, whose capture principle is based on a relative inertial movement produced by a gyroscopic system. Said movement is used to feed a conventional electric generator through several transformation stages of the primary mechanical absorbed energy.

It will also present and discuss the results of the wave tank tests performed in the CEHIPAR facilities with a fifteenth scale model. The model contained a simplified Power Take Off system with the aim of studying the performance of the WEC in regular and irregular waves.

The sea trials were carried out with a quarter scale prototype in the Northern Coast of Spain. The prototype was in commission during a short period of time in summer and autumn so that the sea environmental conditions could be scaled. The goal of these trials was to analyse the structural behaviour of the hull, the data acquisition system and the loads in the lines of the mooring system.

Keywords: Gyroscope, Wave Tank, Sea Trials

Topic 5

Device hydrodynamics and structural mechanics

Hydrodynamic modelling of a vertical axis tidal current turbine using CFD

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Session V-A, Tuesday 15.10–16.15, Gallery A

Results from a computational fluid dynamics (CFD) model of a vertical axis tidal current turbine are presented. This CFD model has been implemented in the commercial code CFX and is a Reynolds-averaged Navier-Stokes solution with the $k-\omega$ SST turbulence model. The turbine simulated is a 15 kW small-scale prototype device being developed by Edinburgh Designs Ltd. with independently and continuously variable pitch blades.

A major focus of the present work is the thorough verification and validation of the numerical model. This is based on a series of progressively more complex simulations, beginning with fixed pitch hydrofoils (airfoils), progressing to oscillating pitch hydrofoils, and finishing with a complete time-dependent model of the turbine.

The paper concludes with a parametric study of turbine performance, comparing fixed pitch and variable pitch operation and a four-bladed variant of the turbine with the three-bladed baseline. It is found that variable pitch operation both increases the peak power coefficient and broadens the peak in the power coefficient versus tip speed ratio curve. An increase in the number of blades (maintaining solidity) leads to a slight drop in performance, commensurate with Reynolds number effects.

Keywords: tidal current turbine, vertical axis, CFD, verification and validation

A parameter study of the influence of struts on the performance of a vertical-axis marine current turbine

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Session V-A, Tuesday 15.10–16.15, Gallery A

Marine currents are an important offshore source of renewable energy. A lot of effort is spent on the development of technology for, for example, electricity generation from tidal currents.

In the present paper, the performance of a vertical axis marine current turbine is examined numerically under the variation of certain parameters.

The turbine is modelled with an in-house code, based on the double multiple streamtube model. Corrections are made due to a finite aspect ratio and tip losses for the blades. Published experimental data for the lift and drag coefficients of the blades for different Reynolds numbers are used in the model.

Structural integrity is a major concern of any underwater machinery due to the considerable hydrodynamic forces involved. Special attention is paid to the importance of struts and related supporting structure for the turbine blades. As a rule of thumb, the efficiency of the turbine may be expected to rise with increased aspect ratio of individual blades. However, with leaner blades more support structure is required, which carries a cost in terms of a negative effect on efficiency. We study how the level of acceptable stress on a turbine blade influences the total turbine efficiency depending on the number of struts required to support the blade.

Keywords: Turbine, blades, struts, simulation

Influence of Solidity on the Performance of a Cross-Flow Turbine

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Session V-A, Tuesday 15.10–16.15, Gallery A

This paper presents a numerical investigation of the influence of solidity on the hydrodynamics of a generic tidal cross-flow turbine. Flows through two- and four-bladed turbines were simulated at a high laboratory Reynolds number, $O(10^5)$. The corresponding turbine solidities were 0.019 and 0.038.

It was found that increasing the number of blades led to an increase in the maximum power coefficient from 0.43 to 0.53. Furthermore, the power curve shifted to a lower range of tip speed ratios due to an increase in flow impedance, and hence reduced streamwise flow velocity, that resulted from the higher turbine solidity.

It was observed that dynamic stall occurred at the lowest tip speed ratios. However, its net effects on turbine performance were found to be negative.

Keywords: Hydrodynamics, Tidal Stream Turbine, Cross-Flow Turbine, Computational Fluid Dynamics, Dynamic Stall

A level set immersed boundary model for extreme wave impacts on wave energy converters

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Session V-B, Wednesday 8.10–9.15, Gallery B

Floating wave energy converters (WECs) are installed at locations with high wave energy and in relatively shallow water where wave nonlinearity is amplified. As a result, wave impact loads constitute a major design consideration for wave energy converters and the violent impact of an extreme wave onto a wave energy converter can be the criterion that determines a number of design parameters. Numerical simulation of the coupled dynamic response of WEC and mooring in storm conditions and under extreme wave loading remains a complex and difficult problem. Nevertheless, quantitative understanding of the wave impact is very important to the efficient performance and long time survivability of a wave energy converter.

A new fully nonlinear CFD technique is developed to assess the wave impacts and dynamic response on wave energy converters. Wave breaking and overtopping occur under extreme wave

loading on offshore WECs. Both the water and air that may be entrained when a wave breaks or overtops a structure should be modelled, and the interface between them defined with a high resolution free surface capturing technique. In this work, a Navier-Stokes equation model is used to simulate the hydrodynamics. A level set method with the global mass correction is developed to study wave breaking and overtopping, and the immersed boundary method is employed to capture the extreme wave loading on offshore WECs.

Calculations have been made for the entry and exit of a cylinder, in which the hydrodynamic force on the cylinder during the first stage of the impact is obtained. The slamming coefficients of the cylinder entry with different entry velocities are calculated and agree well with experimental results. This problem is of importance in the design of various floating structures that experience worst case loading.

Keywords: Level set method, global mass correction, immersed boundary method, wave impacts, wave energy converter, water entry and exit

Extreme Wave Loading on Offshore Wave Energy Devices using CFD: a Hierarchical Team Approach

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Session V-B, Wednesday 8.10–9.15, Gallery B

Many different types of wave energy converters have been proposed in recent years. The two primary design considerations are the need to generate energy at competitive economic rates in average sea states and the need for the wave energy converters (WEC) to survive extreme wave conditions. Due to the complexity of most offshore wave energy devices and their motion response in different sea states, model scale tank tests are common practice for WEC design. Full scale tests are also necessary, but are expensive and only considered once the design has been optimised. Computational Fluid Dynamics (CFD) is now recognised as an important complement to traditional physical testing techniques in offshore engineering. Once properly calibrated and validated to the problem, CFD offers a high density of test data and results in a reasonable timescale to assist with design changes and improvements to the device. This paper deals with the results of test cases leading towards simulation of the full dynamics of Pelamis and the Manchester Bobber. The test cases presented involve the interaction between waves and fixed horizontal cylinders and results are compared with experimental data to validate the CFD codes. Also results for fluid-structure interaction of an oscillating cone on the water surface are presented. The surface elevation and diffraction effects are discussed, as well as the forces on the structures due to the waves and motion respectively. Four different CFD codes are applied to simulate the test cases: Smooth Particle Hydrodynamics, a Cartesian Cut Cell method based on an artificial compressibility method with shock capturing for the interface, and two pressure-based Navier-Stokes codes, one using a Finite Volume and the other a control volume based Finite Element approach.

Keywords: Cartesian-Cut-Cell, FEM, FVM, SPH, Wave-Structure Interaction

Mooring system analysis of multiple wave energy converters in a farm configuration

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Session V-B, Wednesday 8.10–9.15, Gallery B

Like all other floating structures, wave energy converters (WECs) need to be kept in position by station-keeping systems in order to realize its functionality and ensure its safety. A compliant mooring system is normally applied and survivability is the main concern for mooring system design. However, WECs based on relative motions impose special requirements on their mooring systems to ensure that they do not affect the energy capture significantly. The purpose of this study is to investigate possible mooring systems for the FO3 WEC which extracts wave energy based on the principle of relative motions between a platform and multiple point absorbers. The study focuses on the survivability of the mooring system for one WEC and for multiple WECs in a farm configuration under extreme environmental conditions. Coupled time-domain simulation of the mooring system for a single WEC is used and compared with the frequency-domain analysis. An integrated mooring system for nine WECs connected by lines is designed and the dynamic behaviour of the whole system in random seas is analyzed by the time-domain method. Based on the analyses of configurations investigated, it is found that the individual mooring is more feasible than the integrated mooring.

Keywords: Hydrodynamic modelling, mooring system, time-domain simulation, wave energy converter

Optimisation of a Heterogeneous Array of Heaving Bodies

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Session V-B (second half), Wednesday 9.30–10.35, Gallery B

Many of the studies of the interaction factors for arrays of wave energy devices concern systems in which the mechanical damping matrix (R) is specified as exactly equal to the radiation damping matrix (B). Although this represents an ‘optimal’ system of oscillating bodies, the damping and mass conditions required are difficult to engineer. Specifically, for the power generated by an array of bodies that each oscillate in a single mode, the mechanical damping matrix does not replicate the radiation damping which couples adjacent bodies, (R is diagonal whereas B is a dense matrix). Here, analysis is conducted using a frequency domain model based on hydrodynamic coefficients obtained from multi-body WAMIT analysis. We consider a five element array of hemispherical bodies in both terminator (beam-seas) and attenuator (head-seas) configurations in which power is generated from heave of each float only. Mass and mechanical damping are identified for each float to (a) maximize net power from the array and (b) minimize variation of average power across the array. We show that, by selecting appropriate values of damping for each float within the array, power capture can exceed that from an array in which damping is equal to the diagonal of either the radiation damping matrix or of the optimal damping matrix for a constant mass array.

Keywords: Wave Device, Array Interactions, Optimisation

Assessment of the influence of the distance between two wave energy converters on the energy production

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Session V-B (second half), Wednesday 9.30–10.35, Gallery B

In this paper, an array of two interacting wave energy converters with hydraulic PTOs is considered. A time domain model is derived by using classical linear potential theory. Numerical simulations and parametric studies are performed in order to determine the influence of the distance on the capture width of each system in the array, both in regular and irregular waves. It is shown that when the systems are close, the front system (which meets the waves first) is more affected by the wave interaction than the rear system. But the wave interactions decrease faster with the distance for the front system than for the rear system. For this latter system, it seems that the effect of wave interactions remains noticeable even far (14 diameters) from the first system.

Keywords: Wave Energy Converters, Array, Wave interactions, Numerical simulation

Hydrodynamics of triangular-grid arrays of floating point-absorber wave energy converters with inter-body and bottom slack-mooring connections

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Session V-B (second half), Wednesday 9.30–10.35, Gallery B

It may be convenient that dense arrays of floating point absorbers are spread-moored to the sea bottom through only some of their elements (possibly located in the periphery), while the other array elements are prevented from drifting and colliding with each other by connections to adjacent elements. An array of identical floating point absorbers located at the grid points of an equilateral triangular grid is considered in the paper. A spread set of slack-mooring lines connect the peripheric floaters to the bottom. A weight is located at the centre of each triangle whose function is to pull the three floaters towards each other and keep the inter-body moorings lines under tension. The whole system – buoys, moorings and power take-off systems – is assumed linear, so that a frequency domain analysis may be employed. Hydrodynamic interference between the oscillating bodies is neglected. Equations are presented for a set of three identical point absorbers. This is then extended to more complex equilateral triangular grid arrays. Results from numerical simulations, with regular and irregular waves, are presented for the motions and power absorption of hemispherical converters in arrays of three and seven elements and different mooring and power take-off parameters, and wave incidence angles. Comparisons are given with the unmoored and independently-moored buoy situations.

Keywords: Wave energy, Wave power, Arrays, Moorings, Point absorbers

Unsteady 3D Wake Modelling for Marine Current Turbines

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Session V-C, Thursday 9.00–10.05, Gallery A

We present a numerical model for 3D time resolved wake calculations from marine current turbines. Since the wakes are characterised by the shedding of a vortex sheet from the rotor

blades, we have constructed the model based around the vorticity transport equations. A vortex sheet may be considered a jump contact discontinuity in tangential velocity with, in inviscid hydrodynamic terms, certain kinematic and dynamic conditions across the sheet. The kinematic condition is that the sheet is a stream surface with zero normal fluid velocity; the dynamic condition is that the pressure is equal on either side of the sheet. The kinematic condition is satisfied at the trailing edge only, via an approximation of the Kutta condition. The shed vorticity is the span-wise derivative of bound circulation, and the trailed vorticity is the time derivative of bound circulation, and is convected downstream from the rotors using a finite volume solution of vorticity transport equations.

Keywords: Marine Current Turbine, Wake, Unsteady Modelling, Vorticity Transport

Near wake properties of horizontal axis marine current turbines

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Session V-C, Thursday 9.00–10.05, Gallery A

The flow field in the near wake region of a tidal current turbine is strongly driven by the combined wake of the device support structure and the rotor. Accurate characterisation of this region of flow is important but it is characterised by highly turbulent, slow-moving fluid.

Wake flow field characteristics of a 1:20th-scale horizontal axis turbine has been have been measured in a large water channel facility. A downstream map of both the channel base flow and downstream wake was made using both laser and acoustic doppler velocimeters. Wake mapping was conducted with the rotor in both operational an inactive states to quantify the effect of the turbine support structure upon the near wake flow properties.

Results indicate that the wake created by the turbine support structure has a significant effect upon the near wake flow field with strong synergistic effects of both rotor and supporting structure close to the downstream centre plane of the rotor which diminish with increasing lateral (cross channel) distance. Determination of higher order flow properties was difficult close behind the turbine (< 4 rotor diameters) due to extremely high levels of turbulence. Furthermore, it is clear that the form of the rotor support structure has a strong influence upon near wake properties and this will change for the various forms of tidal energy devices either deployed or at the design stage.

Keywords: ADV, Flow, Turbine, Wake

A comparison between CFD simulations and experiments for predicting the far wake of horizontal axis tidal turbines

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Session V-C, Thursday 9.00–10.05, Gallery A

Actuator discs may be used as a simple method for simulating horizontal axis tidal turbines, both in experiments and CFD models. They produce a similar far wake to a real turbine, but eliminate some of the scaling issues which occur in experiments, and reduce the mesh density required in CFD simulations. This paper examines methods for applying a simple actuator disc in a commercial CFD code, Ansys CFX, and compares the wake produced with experimental results for similar values of disk thrust coefficient (C_T). The results show that the CFD model gives reasonable agreement with the experimental results. The main factors affecting the wake structure are the initial C_T value, the ambient turbulence levels, and potentially the disc induced

turbulence. The main differences between the models and experiments were in terms of the turbulence levels throughout the model. With further development, it is considered that the CFD actuator disc could be an accurate and validated method for numerically modelling tidal turbines.

Keywords: CFD, tidal current, turbine, wake

Comparison of boundary-layer and field models for simulation of flow through multiple-row tidal fences

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Session V-C (second half), Thursday 10.20–11.25, Gallery A

A simple conceptual model of an array of tidal stream generators is a series of porous fences subject to flow in one direction, neglecting lateral velocity variations, but allowing for vertical velocity shear. In the far-wake of a fence deep inside the array, the flow might be expected to have reached an equilibrium, where the longitudinal pressure gradient is balanced by the drag of the fences and the friction on the sea-bed. This paper compares two approaches to estimating the downstream decrease in velocity in multiple-row tidal fences; firstly a simplified model using ideas from boundary layer theory previously applied to wind turbine arrays; second, a CFD simulation of the flow field around a ten-row array using a general purpose off-the-shelf RANS Finite Volume solver. The CFD simulations have been themselves compared with measurements gained in a laboratory flume.

Keywords: Tidal power, Tidal streams, CFD, Boundary layers

Inertia Effects on Horizontal Axis Tidal-Stream Turbines

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Session V-C (second half), Thursday 10.20–11.25, Gallery A

This work studies the effects of inertia (added mass) on horizontal axis tidal-stream turbines in unsteady flow. Experiments have been conducted using both an instrumented model rotor and a porous disc as an analogue subjected to unsteady planar (axial) motion in a steady flow water flume. Measurements are presented of the instantaneous axial thrust of the rotor operating at constant torque. Drag and inertia coefficients are calculated for the rotor over a range amplitude parameters (Keulegan-Carpenter number) and rotor operating points (tip speed ratio). These results are compared to Morison's equation for axial force on a body in unsteady flow and also to model predicting dynamic inflow effects. The results provide an insight into the axial added mass and wake effects and they will help our conceptual understanding of these phenomena which overlap, for a rotor operating in unsteady flow.

Keywords: Tidal turbine, Added Mass, Oscillatory Flow, Waves

An experimental study to assess the potential benefits of foundation based flow acceleration structures for marine current energy converters

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Session V-C (second half), Thursday 10.20–11.25, Gallery A

This paper presents a preliminary experimental study investigating the potential benefits of foundation based flow acceleration structures for marine current energy converters. Foundations would provide multiple benefits, including; increased device power output, increased foundation footprint and scour hole protection.

Experiments, scaled from a shallow tidal flow site, provide evidence that these structures could give power benefits of 12–25 % depending on ramp size and flow depth. An optimum ramp size was established based on the suitability of vertical velocity profiles for energy extraction.

Keywords: Tidal flows, flow acceleration, ramp foundation, power gain, velocity profile, ADV

Float Design to Limit Displacement in Severe Seas

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Session V-D, Thursday 13.00–14.05, Gallery A

Many studies have been published concerning the influence of the immersed shape (in still water) of a floating body on its response and power capture from ocean waves. With a few notable exceptions, much of this analysis has assumed small amplitude motion and linear models have been employed to predict response. The form of the upper surface of such a body has received little attention. Here, it is shown that the upper (top) surface of a floating body can be designed to ensure that the response amplitude of the body is within a specified value. This is of considerable importance to the survivability of wave energy devices. The approach used is to affect a large increase of both natural period and hydrodynamic damping for only a small change of float mass. These two factors impose a hydrodynamic limit on the displacement which may be exploited to avoid the 'end-stop' problem often encountered in wave device design. To demonstrate the change of response, experimental measurements are presented of the response of an axisymmetric float with rounded base and conical upper surface with rounded perimeter due to a range of regular, irregular and focused wave conditions. Power extraction is not considered since the mechanically undamped response represents the worst case. In contrast to a simple, straight-sided axisymmetric float, a smaller change of mass is required to satisfy a particular response amplitude limit. Although a significant reduction is not expected, hydrodynamic damping may reduce with increasing physical scale and this remains to be quantified.

Keywords: Wave Energy, Heave Motion, Survivability, Extreme Waves

Hydrodynamic Optimization of the Active surface of a Heaving Point Absorber WEC

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Session V-D, Thursday 13.00–14.05, Gallery A

This paper reports an optimization study to characterize the active surface (surface responsible for the radiation capabilities of the device, i.e., the generation of waves) of an axisymmetric heaving point absorber wave energy converter (WEC). For this purpose several hypothesis

were considered. Firstly, it was assumed the condition for maximum energy absorption with an axisymmetric point absorber. Additionally, a condition to maximize the device radiation capabilities, which consists of the definition of an active surface depth close to the amplitude of the vertical displacement, was also assumed. Following, a final assumption based on a neglectable near body radiation potential at large distances from the wave generator was also taken into account. Finally, based on all the previous assumptions, it was possible to characterize the *WEC* active surface through an expression that relates the non-dimensional active surface radius and depth with the relative excursion of the device. This expression allows to understand promptly the size of an axisymmetric heaving point absorber required to optimize the energy absorption according to the most relevant local wave climate.

To support some hypothesis and simplifications (based on the physical phenomenon) taken into account in this work, a *BEM* numerical code (*AQUADYN*) was applied for additional confirmation [1]. The code is a three-dimensional radiation-diffraction panel model based on the classic linear water wave theory and potential flow.

Keywords: Active surface, heave, excitation, Froude-Krylov, Kramers-Kronig, Haskind, diffraction, radiation, added mass, damping

A hydrodynamic study of a floating circular OWC

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Session V-D, Thursday 13.00–14.05, Gallery A

The development path of a wave energy device from concept to full-scale device is comprised typically of a numerical study and experimental modelling at a number of scales. Numerical models based upon Boundary Element Method (BEM) codes are widely used within the offshore industry and have been validated for fixed Oscillating Water Column (OWC) devices of shoreline type, providing confidence in their use. However, as OWC technology develops and devices are designed for offshore environments, validation of numerical codes for floating OWCs is required. In comparison with characteristic offshore structure design, which aims to minimise motion, wave energy device design has the goal of energy extraction. This may require significant motion, balanced by the power take-off mechanism, and therefore necessitating additional validation for the purpose.

The aim of this paper is to provide a preliminary assessment of the validity of employing a BEM code to predict the displacement and associated hydrodynamic properties of a simple floating undamped OWC in the form of a hollow vertical circular cylinder. Predictions obtained from the WAMIT code are compared with experimental measurements at selected frequencies and with increasing wave amplitude. An investigation of the agreement for predicted and measured pressures is also undertaken.

Keywords: Floating OWC, numerical modelling, experimental modelling, vertical cylinder

Parametric Evaluation of the Performance Characteristics of Tightly Moored Wave Energy Converters for Several Floaters' Geometries

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Session V-D (second half), Thursday 14.20–15.25, Gallery A

The paper investigates the effect that several floaters' geometries have on the performance characteristics of tightly moored vertical axisymmetric wave energy converters. A cylindrical buoy

with and without vertical and horizontal skirts at its bottom, a cone along with two piston-like arrangements, consisting of an internal floater (cone or cylinder) and an exterior torus, have been examined and comparatively assessed. The WEC's first-order hydrodynamic characteristics are evaluated using a linearized diffraction-radiation semi-analytical method. Axisymmetric eigenfunction expansions of the velocity potential are introduced into properly defined ring-shaped fluid regions around the bodies and the potential solutions are matched at the boundaries of adjacent fluid regions by enforcing continuity of the hydrodynamic pressures and radial velocities.

A dynamical model for the floaters' performance in time domain is developed that properly accounts for the floaters hydrodynamic behaviour, the coupling terms between the different modes of motion and of the power take-off mechanism.

Numerical results showing parametrically the effect that the varying hydrodynamic characteristics of each particular floater's geometry have on the investigated WECs performance characteristics are presented and in terms of the expected power production discussed.

Keywords: Converter, Ocean wave energy, Point absorber, WEC

Comparison of damping properties for three different mooring arrangements

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Session V-D (second half), Thursday 14.20–15.25, Gallery A

For the safe operation of floating wave energy converters (WEC's) it is required to obtain deeper understanding of the moored device as a coupled system. The motion of a WEC is dependent on the stiffness, mass and the damping characteristics of the body and the mooring system, as well as influenced by the power take of system. In order to understand the effect of the individual contributions to the coupled system, the influence of the individual parameters needs to be understood. Typical offshore oil and gas installations, in moderate water depths, are often moored using catenary configurations within linear load-extension characteristics. In many applications the damping contribution due to the mooring system is within a linear regime and hence can be applied in a linear fashion. Earlier investigation relating to mooring damping and stiffness can be found in [1-6]

Due to their physical size and the wish to install the WEC in an energetic environment, there is an increased risk that the moor will be operating in a load-extension range with non-linear characteristics. Furthermore, it is likely that for the station keeping of WECs compliant configurations are used with fibre rope sections. These would have an effect on the stiffness and damping characteristic of the mooring system [7,8], which could importantly affect the coupled motion of a moored WEC device. The effect towards the power conversion and/or ultimate peak loads needs to be understood to allow for a safe station keeping that does not adversely affect the energy conversion.

A detailed investigation of mooring line stiffness and damping properties has been conducted at large scale tests in the Scapa Flow at Orkney. Three different mooring arrangements namely, compliant chain, compliant hybrid and nylon rope s-shape were investigated. Preliminary analysis was presented to identify the stiffness characteristics for these large scale mooring tests in open sea environment [9]. This publication presents the continuation of the study by the second author analysing outstanding data from the Scapa Flow test series [9,10,11]. Within the analysis presented here the main focus will be given to the energy dissipation (damping), comparing the different arrangements using the 'indicator-diagram method'. The intention of this study is to identify the damping properties of the individual mooring arrangements in order to provide information towards the analysis of a coupled system.

The outcome will present the dissipated energy (damping) results for the tests and will relate them to the preliminary stiffness analysis. This will then be used to discuss the suitability of

these mooring arrangements with respect to the requirements of different WEC devices. It is also hoped to provide further information on the variability of the damping as a result of a change in frequency characteristics.

Keywords: Mooring line damping, Wave Energy Converter, Large scale testing

Modelling the movement and wave impact of a floating object using SPH

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Session V-D (second half), Thursday 14.20–15.25, Gallery A

This paper investigates fluid and floating object interaction using a novel adaption of the Smoothed Particle Hydrodynamics (SPH) method. This problem is significant to reducing the difficulties of cost-effective designs of wave energy converters, offshore and coastal structures. In particular, this paper investigates water impact, hydrodynamic forces, fluid motions and movement of the object in typical cases of object entry and exit from still water and movement within a surf zone. Conventional grid based models, such as FEM and FDM, are required to generate or adapt the inbuilt mesh at each timestep to conform to the movement of the free surface and the object. SPH is a Lagrangian particle method which does not require a grid, therefore, it is a robust method with which to tackle the problem. The water impact pressure prediction, traditionally considered one of the weaker facets of SPH, shows good agreement with published experimental and numerical results. The hydrodynamic forces exerted on the object, and hence the movement of the object itself, are well predicted. The velocity field of the fluid domain is also captured well. The diversity and results of the case studies provide a good foundation to evaluate the accuracy and stability of using SPH to model the interaction between floating objects and free surface flow, and subsequently to evaluate wave energy capture devices.

Keywords: SPH, floating object, wave energy converter, wave loading, free surface flow, water exit

Investigation of the Influence of Array Arrangement and Spacing on Tidal Energy Converter (TEC) Performance using a 3-Dimensional CFD Model

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This paper details work conducted using the commercial CFD software package Fluent to investigate the influence of different TEC array arrangements. This work investigates the performance variation across a TEC located centrally in an array (measured as a pressure differential). Two scenarios were considered. Firstly, we examined the influence on a central TEC of other TECs in a fixed spacing array and for different configurations (single row array, two-row array with turbines upstream of the central TEC, three-row array with turbine rows both upstream and downstream of the central TEC). Secondly, we examined the influence on a central TEC of other TECs for a given three-row array configuration but considering different latitudinal and longitudinal spacings.

This approach to TEC array modelling does not attempt to conduct detailed modelling of the TEC, but instead examines the variation in the performance of a central TEC as the array is increased row by row. Additional modelling work detailing simulations conducted to investigate

the influence of chosen model parameters and assumptions are also summarised along with a discussion of related uncertainties.

Results of analyses examining the influence of the lateral and longitudinal MCT spacing are presented for a tidal farm array comprising three rows. This work examines the relative effect of increasing the inter row spacing between TEC turbines from 3 TEC rotor diameters to 5 and the row spacing from 10 TEC rotor diameters to 15.

Keywords: Array, CFD, Spacing, Tidal Energy Converter (TEC)

Experimental study to determine flow characteristic effects on marine current turbine behaviour

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This paper presents experimental results from tests carried out in the Ifremer free surface circulation flume tank. The objective of this work is to validate the numerical work conducted under a PhD programme for the characterization of flow perturbations induced by marine current turbines. For that purpose, we used a tri-bladed horizontal axis turbine. The work is dedicated to measure the behaviour of the system and to characterize the wake emitted by the turbine. The efficiency of the turbine is quantified by the measurement of the thrust and the amount of power generated by the rotor for various inflow conditions, while the wake will be characterized by Laser Doppler Velocimetry.

Particular attention is paid to the flow characteristic effects (velocity gradient, flow orientation, etc) on the performance of a 0.70 m diameter turbine. The load predictions on the structure and the measured performance of the turbine over its working range of currents (0.6 to 1.5 m/s) and rotational speed is within 5 % of TGL's analytical model. The trials showed that this kind of turbine is sensitive to the quality of the incoming flow and a misalignment of a fixed turbine can cause significant losses. The turbulence intensity effects on turbine behaviour are also characterized in this paper.

Keywords: Hydrodynamic, marine energy, experimental trials, flume tank, numerical simulations, marine current turbine, turbulence effects

Torque ripple and variable blade force: A comparison of Darrieus and Gorlov-type turbines for tidal stream energy conversion

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

There are two main types of lift driven vertical axis turbine which can be used for capturing energy from tidal streams. These are the straight bladed “Darrieus-type” and the helically shaped “Gorlov-type”. The Darrieus-type turbine can suffer from vibrations in the shaft due to torque variations, known as “torque ripple”. Gorlov-type turbines ought to reduce this problem but suffer from variations in force distribution along the length of turbine blade. The double multiple streamtube model (a blade element momentum model), with the Gormont-Berg adaptation for dynamic stall, is used to analyse the blade forces and shaft torques. The results show the extent to which torque ripple or variable blade force is effected by various other design choices, such as blade thickness, blade camber or turbine solidity. From these some of the requisite turbine characteristics are derived.

Keywords: Tidal Streams, Darrieus Turbine, Gorlov Turbine, Torque Ripple, Variable Blade Force

Hydraulic circuit description of the MGR Wave Energy Converter

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This paper presents the hydraulic circuit of a new wave energy converter (WEC) design, the MGR. The MGR, due to its working principle, is a hydraulic circuit indeed. The MGR is a near shore submerged converter that takes advantage of the oscillating water column created by the wave when it passes on the converter's platform. The wave column pushes the platform, transmitting the force to a single acting cylinder, that pumps sea water to the coast, where is turbined generating electricity.

The study comprises the components definition and the pressure drop in the circuit. The filtered sea water taken from seabed is conducted to the single acting cylinder by a 3-way valve, where it is pumped to the accumulators. The accumulators store pressure energy, to damp cylinder pulses and assure a constant flow. The flow of different modules are collected and sent to the coast through an submerged pipe, where is transformed in electrical energy by a Pelton turbine.

Keywords: hydraulic circuit, pressure drop, resonance with waves, submerged pipe, wave energy

Reduction of the Tip Clearance Effect in a Radial Impulse Turbine for Wave Energy Conversion

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

Radial impulse turbines could be a good option in Oscillating Water Column systems to extract energy from waves. A previous work made by the authors showed that the tip clearance plays a fundamental role in the flow pattern inside the turbine, so seeing the relation between tip clearance's size and turbine performance is a very interesting issue from the point of view of designing this kind of turbomachine.

Evaluate the tip clearance influence on the turbine performance is the purpose of this work. The geometry proposed in (1) with different tip clearance's size and the numerical model described in (2) have been used. The performance comparison shows that changing the tip clearance's size in a 4 % of blade span reduces the stationary turbine efficiency up to 9 %. Although, the influence of the tip clearance in this geometry is not the same in both flow directions, the efficiency reduction is more pronounced when the flow is centripetal.

From a point of view of manufacturing, to decrease the tip clearance has a limit. Therefore a new turbine design that minimizes the tip clearance effects is proposed. The numerical model is used to evaluate the performance of the new turbine.

Keywords: Fluent, OWC, radial impulse turbine, tip flow

Topic 6

Power take-off and device control

Behaviour of a small Wells turbine under randomly varying oscillating flow

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Session VI-A, Wednesday 9.30–10.35, Gallery A

A monoplane Wells turbine was tested during the experiments conducted at sea on a small scale model of a REWEC (Resonant Wave Energy Converter) breakwater. Tests aimed at analyzing the behaviour of the turbine subjected to randomly varying oscillating air flow, variable according to the intensity and spectral characteristics of the sea. During the experimental campaign, 261 records (sea states) were acquired in order to characterize the behaviour of both the plant and turbine. Thanks to the measurement techniques ad hoc developed for tests at sea and described in a companion paper, it was possible to determine the values of torque coefficient T^* and pressure coefficient Δp^* as a function of the flow coefficient, ϕ . Because during each sea state lasting five minutes, data on dozens of cycles of oscillation were recorded, it was possible to perform a statistical analysis of all the available data, with regard to the sign of ϕ and of its derivative. The results were classified by maximum oscillation amplitude and peak frequency of the spectrum. The paper presents the results of the statistical analysis carried out by highlighting the effects on the stall condition at high values of flow coefficient and on the hysteresis between the phases in which the flow rate is growing and those where the flow rate is decreasing. Finally, the influence of the spectral components at higher frequencies on the hysteresis phenomenon was highlighted.

Keywords: Wells turbine, hysteresis, characteristic curves, flow pattern

Evolutionary Algorithms for the Development and Optimisation of Wave Energy Converter Control Systems

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Session VI-A, Wednesday 9.30–10.35, Gallery A

Many strategies have been proposed for the control of wave energy converters (WECs). In order to evaluate these control strategies, they need to be optimised for realistic operating conditions. This paper develops a generic approach for WEC optimisation based on the use of Evolutionary

Algorithms (EAs). A new evolutionary algorithm is developed to efficiently resolve problems found in WEC control. Simulation results are presented for tuning an illustrative device in both sinusoidal and real waves; and for optimisation of ‘slow tuning’, ‘latching’ and ‘fast tuning’ control systems. These results show an increase in the power capture of the device using the optimised control, and demonstrate a convergence to an optimum solution within the constraints presented. In contrast to conventional methods, the proposed EA successfully optimises the control algorithms for realistic seas without prior assumptions. The capabilities of EAs in a “machine learning” setting, in which the control algorithm continues to evolve after installation, are then considered.

Keywords: Wave Energy Converters, Optimisation, Evolutionary Algorithm, Latching, Control

Linear and nonlinear modeling and control of a power take-off simulation for wave energy conversion

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Session VI-A, Wednesday 9.30–10.35, Gallery A

This article focuses on control of the power take off (PTO) element of a point absorber wave energy converter. The research is based on a nonlinear simulation of a PTO hydraulic circuit, in which the piston velocity and generator torque act as ‘disturbance’ and control actuator variables respectively, whilst the damping force is the controlled output variable. The piston velocity is generated by a hydrodynamic simulation model that reacts to both the damping force and sea wave profile. The damping force set point will be obtained from an associated power capture optimisation module and may be time varying. However, it is clear that such an adaptive tuning system also requires high performance ‘low-level’ control of the device actuators, in order to fully realise the benefits of optimisation. In this regard, the present article illustrates use of the Proportional-Integral-Plus (PIP) control methodology as applied to the PTO simulation. In their simplest linear form, such PIP controllers do not account for the interconnected system variables mentioned above. For this reason, the research also considers ‘feed-forward’ and ‘state-dependent’ forms of PIP control, in which the piston velocity is appended to a non-minimal state space representation of the system.

Keywords: SUPERGEN, power take off simulation, optimal control, non-minimal state space

Design of a non-linear power take-off simulator for model testing of rotating wave energy devices

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Session VI-A (second half), Wednesday 10.50–11.55, Gallery A

Eddy current brakes provide a versatile way of simulating the power take-off system (PTO) in the model testing of wave energy converters at small scale. These are based on the principle that a conductive material moving perpendicularly to a magnetic field generates a braking force proportional to its velocity.

This was applied in the design of the PTO simulator of a bottom-hinged flap wave energy converter model, at 1/16 scale. The efforts put into the accurate dynamic simulation of the device led to the development of a controllable PTO simulator, which can be applied to other small scale rotating wave energy device models.

A special power source was built to provide the required controllable current intensity to feed the magnetic field generating coils. Different non-linear damping PTO characteristic curves can be simulated by basing the current control on real-time velocity measurement.

The calibration of the system was done by connecting the device to a constant rotating speed motor and measuring the resistant torque produced by the PTO with a torquemeter for different values of current intensity through the coils.

Keywords: Wave energy, non-linear PTO, experimental modelling, eddy current brake

The influence of a mono-directional PTO on a self-contained inertial WEC

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Session VI-A (second half), Wednesday 10.50–11.55, Gallery A

This paper looks at the effect that a mono-directional Power Take Off (PTO) has on the motions and power extraction of a Wave Energy Converter (WEC). A monodirectional damper is one where the resisting force only operates in one direction. The model comprises of a cylinder that is restrained to move in heave, reacting against an internal mass (also limited to move in heave) that is connected to the cylinder by a spring and monodirectional damper in parallel.

This paper presents experimental results for a variety of different damping constants for mono-directional dampers which operate in both in expansion and compression. The response amplitude operators to monochromatic waves for both the cylinder, the internal mass and the relative motion between them are presented. A Pierson Moskowitz spectrum is used to look at the effect of an irregular sea state and the power extraction is calculated from this spectrum. The results show a greater response of the cylinder, but also in certain cases the internal mass and relative motion, when a mono-directional damper is present than when there is no damper. It is postulated by the authors that this is due to a “latching” effect. This increase in motion results in a greater than expected power extraction.

Keywords: Experimental wave tank testing, Nonlinear Power Take Off, Inertial point absorber, Wave Energy Converters (WECs)

Investigating the Performance of a Hydraulic Power Take-Off

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Session VI-A (second half), Wednesday 10.50–11.55, Gallery A

Many wave energy converter (WEC) developers are in the process of scaling up previous point absorber concepts to 100 kW+ devices. As sizes increase, serious challenges in power take off (PTO) design are being encountered. Hydraulic transmissions are favoured as gearing up to give high speed rotary motion is easily achieved, and power density is high.

They are also highly controllable, for example allowing take-off cylinders to be locked or free-running as conditions require via simple valve control. Theoretical concepts for extracting the maximum power from waves already exist, using reactive or latching control for example, but these do not account for the real engineering limitations or losses in practical PTO systems. The concepts assume that the PTO can generate any given force/motion relationship with equal efficiency.

This paper presents the results of a simulation study on the design and control of a hydraulic PTO. The control strategies for maximum power extraction are compared with and without

consideration of the characteristics (losses) in the PTO. It is shown that efficiency can be surprisingly low. It is also shown that using components (motor and pump in this case) sized for smaller wave conditions may be preferable as their efficiency is better.

Keywords: wave energy converters, power take-off, hydraulics

Wave Farm Design: Preliminary Studies on the Influences of Wave Climate, Array Layout and Farm Control

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Session VI-B, Thursday 9.00–10.05, Main hall

In this paper preliminary results regarding the assessment of the energy absorption characteristics of an array of wave energy converters (also referred to as a wave farm) are presented. Regular and irregular waves are used as input in a frequency domain hydrodynamic model which allows iterations in the array layout and farm control strategy. Under such an approach each array element can be controlled independently while keeping the design objective (maximisation of the wave farm energy yield).

The approach is initially verified by comparing the solution of the radiation and diffraction problems for the array with the analogous results from a semianalytic method developed at the University of Oxford. Additional regular wave simulations identify the most promising areas by quantifying the interaction factor as a function of the incident wave frequency and wave heading. Irregular waves which describe representative frequency spectra are then used as input to quantify the power absorption characteristics from an isolated wave energy converter. Finally, the same representative seas are used as input when evaluating the energy absorption by an array of wave energy converters, while iterating on the array layout and control settings associated with each array element.

The overall objective of the study is to quantify the influence of the array layout and farm control in the performance of a wave farm under the action of irregular waves. The results show that the energy yield is affected by such factors, hence these can be seen as key design drivers when considering the potential for reduction in the uncertainty and thus the cost of energy associated with a wave farm. Further studies may address additional constraints, either technical or economical. This study is expected to contribute to the development of specific modules of GH WaveFarmer, a tool that aims to optimise the design of wave farms.

Keywords: floating bodies, hydrodynamic interactions, wave farm

Control Strategies for a simple Point-Absorber Connected to a Hydraulic Power Take-off

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Session VI-B, Thursday 9.00–10.05, Main hall

Among the various types of wave energy converters currently being developed, heaving point absorbers are one of the simplest and most promising concepts, possibly due to their ease of deployment and integration in larger arrays structures.

A typical efficient energy conversion system for point absorbers is based on hydraulic power take-off (PTO) systems, consisting in a double-acting cylinder and two or more accumulators,

reserving fluid at different pressures and linked between them by a hydraulic motor connected to an electric generator. For the purpose of control and modulation of the power output the hydraulic circuit might include a certain number of valves that can set the pressure levels within the accumulators.

This paper presents a simple model of a heaving oscillating buoy, represented by a surface-piercing cylinder, extracting power by means of a hydraulic system. The hydrodynamic behaviour of the absorber is modelled through application of the linear water wave theory. Apart from the basic elements listed above, the model of the hydraulic system includes leakages and pressure losses and takes into account the compressibility of the fluid. Also possible extra accumulators are considered in order to improve the performance of the hydraulic system by means of properly controlled valves. The function of these extra accumulators consists in storing and releasing energy to the system when this is desirable for the improvement of the power output.

Simulations were carried out through a time-domain approach making use of the Cummins equation and considering regular monochromatic waves and irregular wave-trains.

The control of the system is managed by means of control valves whose opening will be depending on the sign of the velocity of the buoy and the pressure levels. Three possible aims were assumed for the control strategies investigated: maximisation of the average power output, stabilisation of the output (in terms of rotational velocity and/or electrical power) and stabilisation of the pressures inside the accumulators (also for survivability of the hydraulic equipment). Different control variables are analysed depending on the wave inputs considered in order to improve the power extraction of the converter: Firstly the torque of the electric generator is considered as a primary way to modify the load of the PTO. Then extra accumulators are used as storing devices to perform a kind of phase control on the buoy. The benefit of this effect will be dependent on the instant of activation of the valves that connect them to the circuit and the influence of possible delays or anticipations will be investigated.

The results prove that it is possible to achieve a great enhancement of the power extraction with the implementation of these control strategies and that a possible combination of some of them might be beneficial for a better efficiency of the components. Moreover the application of sophisticated strategies could imply a less demanding requirement for specific equipments; such as the case of the electrical generator.

Keywords: Hydraulic PTO, phase control, point absorber, wave energy converter

A Study on Short-Term Sea Profile Prediction for Wave Energy Applications

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Session VI-B, Thursday 9.00–10.05, Main hall

Control of wave energy converters requires knowledge of some seconds of the future behavior of certain physical quantities, in order to approach optimality. That is why short time prediction of the oncoming waves is a crucial problem in the field of wave energy, whose solution could bring great benefits to the effectiveness of the devices and to their economical viability.

This study is proposed as a preliminary approach to cope with this necessity, where wave forecasts are computed on the basis of past observations collected at the prediction site itself. Working on single point measurements allows the treatment of the wave elevation as a pure time series, so that a wide range of well established techniques from the stochastic time series modelling and forecasting field may be exploited. Among the proposed solutions there are some cyclical models, based on an explicit representation of the *a priori* knowledge about the real process. It is then shown how a lot simpler and more effective solution can be obtained through classical AR models, which are shown to be able to implicitly represent the cyclical

behavior of real waves. As a comparison with AR models some results obtained with neural networks are also provided.

Keywords: wave energy, control of wave energy converters, wave forecasting, time series

Integrated Structural and Electrical Design of the Linear Permanent Magnet Synchronous Machine

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Session VI-B (second half), Thursday 10.20–11.25, Main hall

Linear permanent magnet generators are a potentially useful technology for wave power applications. Typically, optimisation and comparison of these generators is based on an electromagnetic analysis with limited regard for the structural analysis. This paper presents a comparison of two alternative designs of the double-sided linear permanent magnet synchronous machine which includes structural and bearing requirements for a more accurate assessment of cost and feasibility. It is shown that both cost and feasibility depend heavily on these issues due to the large internal and external forces acting on the machine.

Keywords: Direct-drive generator, linear synchronous machine, permanent magnet machine, wave energy converter

CFD Analysis of Air Turbines as Power Take-Off Systems in Oscillating Water Column Wave Energy Conversion Plant

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Session VI-B (second half), Thursday 10.20–11.25, Main hall

This paper presents the results of CFD simulations of reversing flow air turbines used as the power take-off system in Oscillating Water Column (OWC) Wave Energy Conversion (WEC) plant. One of the simpler tools to analyse such turbines is the blade element/actuator disc methodology. This requires the input of “interference factors” to model how the lift and drag characteristics of the cascade of blades on the turbine rotor are related to those of a single isolated aerofoil. In the first part of the paper, CFD modelling to obtain the lift and drag characteristics of various aerofoils arranged in linear cascades at different stagger angles is described. The CFD cascade lift and drag data are compared with reported experimental cascade aerodynamic data. The agreement within the range of usable stagger angles is excellent in the pre-stall range with some deviations shown in the post-stall. A comparison is also made between our 2D CFD interference factors and those previously reported by Weinig and others who used analytical, inviscid flow theory. It is found that the Weinig inviscid flow theory provides a reasonable prediction of the lift interference factor providing that both the angle of attack is relatively low and that the thickness of the blades is relatively small compared to the distance between blades. In the second part of the paper, three-dimensional simulations of a Wells air turbine rotor using CFD unstructured and structured grid designs are described. The results of the three-dimensional CFD simulations were then compared with those from our non-dimensional blade element model incorporating the linear cascade aerodynamic data described in the first part of the paper. The two sets of results are compared in terms of torque coefficient and pressure coefficient.

Keywords: air turbine, blade element, computational fluid dynamics, cascade, aerofoils, variable pitch, wave energy

Applications of Supercapacitor Energy Storage for a Wave Energy Converter System

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Session VI-B (second half), Thursday 10.20–11.25, Main hall

As wave energy converters (WECs) continue their development, improved performance using various energy storage options are constantly being examined.

This paper describes the applications of an energy storage system based on supercapacitors in a full-scale, grid-connected offshore WEC. The following areas are examined: Minimisation of the output power fluctuations; start sequences for the machine; and Low-Voltage Ride-Through (LVRT) capability. Focus is placed on ensuring a component lifetime greater than the maintenance period of the WEC. The investigation is based on a Backward-Bent-Duct Buoy (BBDB) Oscillating Water Column (OWC) using a Wells turbine connected to a Permanent-Magnet Synchronous Machine (PMSM) as the power take-off. The full system is modelled in Simulink using real sea data, and results are shown.

Keywords: Lifetime, LVRT, supercapacitors, WEC

Stochastic, time domain models and Pontryagin Maximum Principle for a two body wave power device

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

In this study a stochastic model to describe the behaviour of an articulated system is developed. Optimal mechanical damping and spring coefficients are computed. Probability density functions are defined for the relevant parameters that characterize the device behaviour. For these parameters and for different sea state conditions the probability density functions are found and the articulated system is characterized in terms of these functions. Average values for useful power and capture width are also obtained for these sea state conditions.

Time domain models allow the computation of time series for the variables that characterize the wave power system behaviour. In this study a time domain model is also developed for the articulated wave power device. Results are obtained for regular and irregular waves.

Pontryagin Maximum Principle is presented as an algorithm for the control of the device.

Keywords: stochastic modelling, time domain modelling, Pontryagin Maximum Principle, two body device

Performance of closely spaced point absorbers with constrained floater motion

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The performance of a wave energy converter array of twelve heaving point absorbers has been assessed numerically in a frequency domain model. Each point absorber is assumed to have its own linear power take-off. The impact of slamming, stroke and force restrictions on the power absorption is evaluated and optimal power take-off parameters are determined. For multiple bodies optimal control parameters are not only dependent on the incoming waves, but also on the position and behaviour of the other buoys. Applying the optimal control values for one

buoy to multiple closely spaced buoys results in a suboptimal solution, as will be illustrated. Other ways to determine the power take-off parameters are diagonal optimization and individual optimization. The latter method is found to increase the power absorption with about 14 % compared to diagonal optimization.

Keywords: array, constraints, multiple bodies, point absorber, wave energy

Experimental methods for Power Take-off (PTO) simulation of a Wave Energy Converter (WEC)

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The objective of this paper is to describe one of the R&D stages of Martifer's WEC.

It is well known that one of the major difficulties in experimental wave testing is the reduced scale used and its implication on the typical methods utilized to determinate the possible energy conversion, as well as the methodology used to characterize the performance of a new WEC concept [1]-[2].

The WEC's concept and geometry were obtained using hydrodynamic analysis of several shapes and also in conformity with preliminary downscaled tests in regular wave states.

The main goal of these experimental tests were to simulate and observe the interactive behaviour of different configurations and methodologies for converting wave energy into usable energy, designated as its PTO system. In order to achieve this, several methods of growing complexity and accuracy were used to simulate the PTO system, from simple springs to more complicated friction based and compressed air type systems were used.

Described herein are the first set of tests, which include the limitations of the methods used, their results and the most relevant conclusions.

Keywords: experimental tests, methodology, Power take-off, PTO, Wave Energy Converter, Wave tank, WEC

Topic 7

Device and environmental modelling

Numerical modeling of a river site for in-stream energy converters

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Session VII-A, Tuesday 12.30–13.35, Gallery B

Current measurement in the river Dalälven, situated in Sweden, was compared with flow values. These were also used to validate a numerical simulation of the channel. The results showed the numerical program was able to assess the current speed variations, but the magnitude of the current speed was slightly lower than the measured values, a possible effect of bathymetry errors. The water level variations were not correctly assessed, which is probably due to that wind data was excluded.

The numerical program was used to evaluate how large the effects on the surrounding water level and current speed can be for a set of ten turbines distributed evenly along the channel. To investigate how the hydrography of the channel is affected by energy extraction, a set of ten turbines distributed evenly along the channel were put into the numerical model. It showed that extracting 75 kW would increase the water level at the power station (upstreams) from the level at the same place without any turbines with 5.5 %, and 135 kW would lead to an 8.8 % increase, assuming a constant water level at the downstream boundary. With increasing c_d -values, the velocity around the turbines increases, while it decreases at the turbine.

Keywords: numerical modeling, river, energy conversion

Experimental and Computational Analysis of a Model Horizontal Axis Tidal Turbine

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Session VII-A, Tuesday 12.30–13.35, Gallery B

Tidal stream turbines provide a predictable and sustainable source of energy. They can be sized to suit the requirements of the local environment, and can be placed in either an individual or 'farm' configuration. The work described in this paper provides CFD validation data from a series of laboratory tests undertaken on a scaled model of a horizontal axial tidal turbine (HATT). The laboratory tests used a 0.5 m diameter three bladed turbine in a water flume which

had a uniform flow profile with a magnitude of 1 m/s (~ 2 knots). Experimental data for power and torque were generated using a Baldor servomotor, load and control system. The motor's speed and torque were controlled and logged. The power and torque data are compared to that produced from a series of CFD models of the same turbine, rotating over the full range of angular velocities with the flume boundary conditions, using the software package FLUENT. The comparative study shows that the CFD models provide excellent predictions of power and torque.

Keywords: CFD, HATT, power, torque, water flume

The Effect of Boundary Conditions on Performance Prediction Model Results for Tidal Turbines

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Session VII-A, Tuesday 12.30–13.35, Gallery B

Aerodynamic models are typically used to model tidal turbines but the differences between wind and tidal turbines are such that these models may not accurately represent the performance of a tidal turbine. Aerodynamic models assume free flow whereas in a tidal channel the channel boundaries are likely to have an effect on turbine performance. Models for flows with three different boundary conditions have been developed in order to demonstrate how significant the effect of the boundaries is. The first model is the classic aerodynamic model, the second considers flow in which all the boundaries are rigid and the third considers a channel where the free surface can deform. The effect of channel area to turbine area on performance has been investigated using these models. The results from the models indicate that the boundary conditions assumed in the model have a significant effect on the predicted performance of the turbine. The difference between the model results increases as the tip speed ratio increases and as the ratio of channel area to turbine area is reduced. The model results suggest that for realistically sized devices in actual tidal channels, aerodynamic models will not provide an accurate prediction of the performance.

Keywords: Blade Element momentum, Performance prediction modelling, tidal turbine

Frequency domain techniques for numerical and experimental modelling of wave energy converters

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Session VII-B, Wednesday 13.30–14.35, Gallery A

This paper discusses the restrictions on frequency domain modelling of wave energy converters (WECs). It is shown that, for a model where the radiation is represented as causal, and where the control signal is not acausal, a frequency domain model is suitable for finding the post-transient, linear, causal response of a WEC. The common use of models that do not represent the casual nature of radiation (memory), or that include an acausal control signal, are identified in the literature. Arguments are presented for restricting both models to sinusoidal motion. Correct and incorrect applications of these restricted models to numerical and experimental work are discussed, with examples given from literature. Several papers are identified that could be interpreted as stating that frequency domain modelling of WECs is restricted to sinusoidal motion only. However, it is shown that these papers are in fact discussing the limitations of

models where the control signal, or the WEC itself, are represented as mass-spring-damper systems.

Keywords: wave energy, frequency domain, monochromatic

Hydrodynamics and absorption efficiencies of wavemakers

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Session VII-B, Wednesday 13.30–14.35, Gallery A

For most of the twentieth century naval hydrodynamics, and more recently, wave energy hydrodynamics have been limited to the realms of theory and physical experiments. Both of these methods of fluid flow analysis are constrained through scope, cost and size of facility. The advent of high speed digital computing has brought with it a new dimension for analysing fluid flows, that of numerical modelling. This paper aims to harness this progress in computing power and established commercial computational fluid dynamics (CFD) codes to create a numerical analogue to the physical test flumes that are in operation in many hydrodynamic labs. Using numerical wavemakers will allow for the use of different shaped wavemakers that would be otherwise impossible to implement in a physical waveflume, these non-conventional shapes will be investigated.

This paper presents the well established wavemaker theory. This is then adapted to obtain the hydrodynamic coefficients of added mass and damping for two novel shaped wavemakers. The different wavemaker geometries are compared on the basis of their theoretical wave absorption efficiencies at various tuned frequencies. Wavemaking simulations using ANSYS CFX are then presented and the results are discussed.

Keywords: Wavemaker, CFD, absorption, added mass, damping

Algorithm for the search of the secondary converter optimum impedance in a punctual wave energy converter

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Session VII-B, Wednesday 13.30–14.35, Gallery A

In this work an algorithm is presented with the purpose of calculating the design requirements that can be imposed to the secondary converter (composed by the electrical generator and other mechanisms) in order to allow the buoy of a wave energy converter system to extract the maximum power from the ocean in each scenario. The physical simulations are carried out by a Simulink model, coupled with a Matlab code that performs the optimization of the generated power.

Keywords: heaving buoy, wave energy converter, power optimization

A wear model for assessing the reliability of wave energy converter in heave with hydraulic power take-off

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Session VII-B (second half), Wednesday 14.50–15.55, Gallery A

Understanding and managing the safety and reliability issues of ocean energy converters is a key factor in the development of viable technologies. This requires mathematical models that

enable numerical solution with the sufficient accuracy and computational efficiency. In this study a point absorber has been chosen as an example of a wave energy converter (WEC). The converter has been modelled by using bond graphs – a systematic and useful method for systems spanning several energy domains.

In the hydraulic system of the WEC, the piston ring and cylinder play very important roles in achieving desired energy converting performance and durability. In this paper, an abrasive wear model for the piston ring and cylinder is developed during the steady state operation by using the Archard's abrasive wear equation. Based on time domain simulation results for the full conversion system, the development of wear in the piston ring is modelled as a function of the contact pressure and relative motion. The procedure to determine the time to failure due to the scuff for the ring is calculated for a case with one sea state only.

Keywords: bond graph, abrasive wear, wave energy converter, piston ring, hydraulic piston pump

Analysis of potential power output of a device using a wave-by-wave approach

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Session VII-B (second half), Wednesday 14.50–15.55, Gallery A

The assessment of energy production from a wave energy converter commonly uses a stochastic approach. For short-term evaluations, a sea state can be represented in the frequency domain by an energy density spectrum. If a suitable frequency-dependent transfer function for the device is defined, an estimate of the total energy output for that specific sea state can be made. However, using a spectral averaging of the sea state in this way fails to account for short-term events that may significantly alter the output estimated using the spectral approach.

This paper uses a 'wave-by-wave' method to assess the potential energy production of a hypothetical device, using recorded time series of sea surface elevation. The device is modelled as a damped linear oscillator, with the assumption that the device can be rapidly 'retuned' to maximise its response to changing wave properties. The method involves calculating the power output for each individual wave in the time series for a range of tuning rates and power transfer function (PTF) bandwidths. The average power output for each time series is then compared with estimates made using the traditional spectral method. The results illustrate the extent to which the estimates of power output differ depending on the rate of tuning and bandwidth of the PTF.

Keywords: device tuning, power output, power transfer function, Wave Hub, wave power

Mean Power Output Estimation of WECs in Simulated Sea

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Session VII-B (second half), Wednesday 14.50–15.55, Gallery A

Based on linear wave theory, two ways of simulating wave records from target spectral densities are implemented in order to assess their impact on the estimation of the mean power extracted from waves by a resonant Wave Energy Converter (WEC). The first one directly comes from the random Gaussian wave representation, while the second – widely used – derives from this latter by abusively neglecting the random nature of the individual wave amplitudes in the frequency-domain. This study investigates the consequences of such an abuse upon the device's response estimation through the consideration of various – linear and non-linear – numerical models,

and the possible improvements of the simulation time/precision compromise for further WEC design projects.

Keywords: Wave signal simulation, Gaussian signals, Wave-Energy Converter, Mean power estimation

Research for evaluating performance of OWC-type Wave Energy Converter “Backward Bent Duct Buoy”

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Session VII-C, Thursday 13.00–14.05, Gallery B

In 1986, Masuda proposed a floating wave energy converter with oscillating water column and it was named Backward Bent Duct Buoy (BBDB). In order to design a floating OWC-type wave energy converter such as BBDB optimally, it is necessary to develop a numerical analysis code in time domain on motions of BBDB, air flow in air chamber and rotation of air turbine in waves. As a first step for developing such numerical code, in this paper, first, equations of motion of a floating OWC-type wave energy converter in waves considering memory effect by air pressure in air chamber are shown. Second, some calculation results in frequency domain by 3D boundary element method, which are a base of above calculation in time domain, are shown. Experiments on exciting forces and radiation forces are also carried out and calculation results are compared with experimental results in frequency domain. In addition, BBDB has negative drift force in specific frequency region and it is important to estimate mooring cost for practical use. However, detail on it is still not clear. So, to make it clear experimentally, four kinds of tank tests were carried out and discussed in this research.

Keywords: Backward Bent Duct Buoy, Drift Force, Hydrodynamic Coefficients

Experimental verification of the stochastic model for predicting the performance of Oscillating Water Columns devices

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Session VII-C, Thursday 13.00–14.05, Gallery B

Stochastic models are often used to evaluate the average power output of an oscillating-water-column (OWC) wave power plant equipped with a Wells turbine and for defining optimal control criteria of the system. The application of the stochastic model to OWC devices is based on the hypothesis that the dynamic behavior of the system can be modeled by a set of linear differential equations and that the sea surface elevation, acting as an input, has a Gaussian probability density function. Under such hypotheses, from the theory of the random processes of the linear systems, it comes that the outputs of the system, such as the pressure in the chamber and the turbine flow coefficient, have a gaussian distribution. Actually, there are several non-linear phenomena that can alter the linear behavior of a OWC device:

- minor and major losses of the unsteady flow of water and air;
- compressibility of air and heat exchange with the walls of the air chamber;
- non-linear characteristics of the turbine.

The stochastic model can be applied if such nonlinearities have, on the whole, limited effects or if a specific procedure able to take them into account is adopted, as suggested by the authors in previous papers.

In the Authors’ knowledge, no experimental validation of the application of the stochastic model to OWC devices are present in the open literature.

This work, making use of data gathered during the experiment on a 1:10 scale model of a ocean OWC breakwater, put at the sea off the beach of Reggio Calabria, aims at verifying that the energy conversion process inside the OWC can be actually described as a gaussian process. To this purpose, the frequency distribution of the main physical parameters, relevant to the system dynamics, are evaluated. Moreover, in order to characterize the behavior of the Wells turbine, the experimental values of the time averaged turbine torque and pressure drop are evaluated as a function of the variance of the flow coefficient. The results show a very high level of correlation and a very good agreement with those that can be obtained from the application of the stochastic model, using as an input the characteristic curves of the turbine, yielded in the unsteady flow.

Keywords: breakwater converter, stochastic approach, linearized model, Wells turbine, random waves

Modelling and Analysis of an Offshore Oscillating Water Column Wave Energy Converter

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Session VII-C, Thursday 13.00–14.05, Gallery B

This paper investigates the modelling of a quarter scale offshore oscillating water column (OWC) wave energy converter (WEC) with results from a prototype device used to validate the model. The OWC WEC utilises a specialised bi-directional air turbine known as the Wells turbine. The paper investigates the modelling of this turbine and studies the electrical output from a generator to be coupled to the turbine. Simulations of the proposed system are carried out under multiple sea state conditions and are compared to results from the prototype device located at an experimental test site in Ireland.

Keywords: Electical Machines, Device Control, Wells Turbine Modelling

Comparison of Wave Power Extraction by a Compact Array of Small Buoys and by a Large Buoy

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Session VII-C (second half), Thursday 14.20–15.25, Gallery B

Wave Energy Converters (WEC) are usually designed to achieve maximum efficiency by impedance matching with the incoming waves. We first review the typical features of a heaving buoy. One feature is that the buoy must be large enough in order to resonate in the usual frequency range of the sea waves. Another is that the frequency range of high efficiency is band-limited, as in many other devices based on impedance matching. Inspired by the FO3 system being developed in Norway by Fred Olsen and ABB Associates, and the Manchester Bobber from UK, we examine theoretically power extraction by a compact array of small buoys. It is shown that such systems have certain advantages over a single large buoy.

Keywords: Homogenization, linear hydrodynamics, wave energy, water waves

Transformation of Wave Spectra across a Line of Wave Devices

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Session VII-C (second half), Thursday 14.20–15.25, Gallery B

As the deployment scale of wave farms increases towards hundreds of MW installed capacity, it becomes important to understand how nearshore coastal processes may be modified by energy extraction. Most of the published studies on the environmental impact of wave energy converters represent a group of devices using transmission and absorption coefficients. This approach represents the average energy extraction across the power spectrum but, since wave device performance is dependent on the wave frequency, the use of frequency-dependent transmission coefficients may be more appropriate. In this study, SWAN is used to investigate how the definition of a frequency-dependent transmission coefficient, based on an idealised point absorber, alters nearshore conditions relative to a constant transmission coefficient. Experimental measurements are also presented to quantify the change of wave characteristics due to a small array of heaving point absorbers. Wave spectra measured down-wave and up-wave of arrays comprising five- and ten- devices are compared to those measured at the same location prior to device deployment. The influence of these modifications on breaking conditions near the shoreline is briefly discussed and the measurements provide the basis for evaluation of numerical models of device arrays at the site scale.

Keywords: Spectrum changes, WEC, Nearshore

Experimental Measurements of Irregular Wave Interaction Factors in Closely Spaced Arrays

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Session VII-C (second half), Thursday 14.20–15.25, Gallery B

Much of the published work concerning the response and power output of closely spaced arrays of heaving wave energy devices concerns behaviour in regular waves only and is based on numerical analysis. To date, limited experimental work has been published and it remains unclear how device interactions predicted in idealised models relate to the response of proposed devices in realistic irregular wave-fields. Experimental measurements of the power absorbed by a small two-dimensional array of heaving devices in both regular and irregular waves in a wide flume are reported. Under certain conditions, positive interactions (where the average power output of the array exceeds the same number of isolated devices) are measured. Initial measurements suggest that positive interactions correspond to individual float displacements much larger than the incident wave amplitude. From regular wave tests, the presence of positive interactions is largely dependent on the incident wave period and the performance of adjacent devices. Preliminary tests indicate that float responses tend to be smaller when subjected to short period irregular waves of equivalent peak frequency. The data presented provides an insight into interactions within irregular wave conditions and forms a basis for evaluating numerical models.

Keywords: Interaction factor, Irregular wave, Experimental, Array

Numerical simulation of wake effects in the lee of a farm of Wave Dragon wave energy converters

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The contribution of wave energy to the renewable energy supply is rising. To extract a considerable amount of wave power, Wave Energy Converters (WECs) are arranged in several rows or in a 'farm'. The wake behind each individual WEC in the farm affects the power absorption of its neighbouring WECs.

In this paper wake effects in the lee of a single Wave Dragon WEC and multiple Wave Dragon WECs are studied in a time-dependent mild-slope equation model. The Wave Dragon WEC is a floating offshore converter of the overtopping type. The water volume of overtopped waves is first captured in a basin above mean sea level and then drains back to the sea through hydro turbines.

The wake dimensions behind a single Wave Dragon WEC are investigated for uni- and multidirectional waves. An increasing directional spreading results in a faster wave redistribution behind the WEC. The power absorption of a farm of five Wave Dragon WECs, installed in a staggered grid, is calculated for varying inbetween distances. It is observed that an in-between distance of 2D is preferred, when taking spatial and safety considerations into account.

Keywords: farm, mild-slope equation, wake, wave energy

Numerical Modelling of a Surging Point Absorber Wave Energy Converter

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This study presents numerical modelling of a WEC (wave energy converter) along with some details of the experimental setup. Issues related to the numerical modelling of the single DOF (degree-of-freedom) motion of a surging point absorber WEC are outlined and a comparison with experimental data is presented. A commercial CFD code Flow-3D is used for numerical modelling and the ability of the code to simulate free surface linear waves and wave structure interaction is evaluated.

The work is aimed at simulating a surging wave energy converter to achieve an optimized shape and to predict output power at a higher or full scale. The findings of this study may also serve as a reference point for the use of a commercial code such as Flow-3D for the simulation of such problems.

Keywords: CFD, Numerical modelling of Wave Energy Converter, Flow-3D, Surging Point absorber

Influences of wave directionality on a generic point absorber

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The present study deals with the influences of wave directionality on a generic point absorber. The work presented here, shows how the dynamic of axisymmetric wave energy converter can be affected when one consider a realistic wave spectrum. For this purpose a non linear numerical

model was used. The fluid structure interactions are modelled by means of a bending method where the Froude-Krylov forces are non linear and the radiation-diffraction problem is solved by using a linear method. Mooring loads are modelled via a finite element method. A compliant catenary mooring system composed by 4 mooring lines is hence used. Different models of sea spectra are used to approximate a real sea spectrum. The differences between them are discussed and comparisons on the body motions are commented.

Keywords: Point absorber, wave energy, random sea, mooring system

Modelling of the MGR Wave Energy Converter

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The paper concerns the development of a non-linear model of the MGR. The linear wave theory has been modified, simplifying the wave input form (sinusoidal) and disregarding the radiation component of the hydrostatic force. The storage stage of accumulators has not been taken into account.

The MGR is a near shore submerged converter that takes advantage of the oscillating water column created by the wave when it passes on the converter's platform. The wave column moves the platform, transmitting the force to a single acting cylinder, that pumps sea water to the coast, where is turbined generating electricity.

The model has been made using the MatLab's Simulink module. The aim of the model is to asses the working principle, validating the variable system pressure control strategy. The results have been as expected with small waves, overlapping cycles as wave size increases.

Keywords: Wave energy, simulation, modelling, near shore device, resonance with waves

Prediction of the individual wave overtopping volumes of a wave energy converter using physical modeling and first numerical model results

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

For overtopping wave energy converters (WECs) a more efficient energy conversion can be achieved when the volumes of water, wave by wave, that enter their reservoir are known and can be predicted. A numerical tool is being developed using a commercial CFD-solver to study and optimize the hydrodynamic behavior of overtopping WECs, which includes the prediction of the individual overtopping volumes.

This paper presents the results of experimental model tests that have been carried out to validate the numerical tool for its ability to predict the individual overtopping volumes for a fixed nearshore 2D-structure. First numerical model results are given for a specific test with regular waves, and are compared with the corresponding experimental results in this paper.

Keywords: device control, numerical CFD models, overtopping, physical model tests

Topic 8

Testing standards and performance normalization

Toward reliable production estimation from Wave Energy Converters

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

This paper presents a PhD project aimed to improve the reliability of production estimation of Wave Energy Converter from the performance description and the statistical description of a wave climate.

So far, a review of the different spectral parameters has been done. The parameters were then chosen regarding their relevance to wave energy conversion and how they combine to describe the directional spectrum. Using pseudo-deterministic methods (single summation), the generation of the sea states corresponding to the desired values of each parameter is an ongoing process.

Accurate measurement of the wave spectrum inside the tank is an important part of the project. A version of the MMLM [1] specially implemented to make use of deterministic waves is developed. Emphasis is put on the design of an optimal gauge array. The method is currently tested against virtual data and early results on the array design are presented.

Keywords: tank testing, production estimation, directional spectrum, Maximum Likelihood Method

Topic 9

Environmental impact and appraisal

Underwater Noise Modelling of Wave Energy Devices

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Session IX, Thursday 13.00–14.05, Main hall

Future large-scale implementation of wave energy converts (WECs) will introduce an anthropogenic activity in the ocean which may contribute to underwater noise. The Ocean houses several marine species with acoustic sensibility; consequently the potential impact of the underwater noise needs to be addressed. At present, there are no acoustic impact studies based on acquired data. The WEAM project (Wave Energy Acoustic Monitoring) aims at developing an underwater noise monitoring plan for WECs.

The development of an acoustic monitoring plan must consider the sound propagation in the ocean, identify noise sources, understand the operational characteristics and select adequate instrumentation.

Any monitoring strategy must involve *in-situ* measurements. However, the vast distances which sound travels within the ocean, can make *in-situ* measurements covering the entire area of interest, impracticable. This difficulty can be partially overcome through acoustic numerical modelling.

This paper presents a synthetic study, on the application of acoustic forward modelling and the evaluation of the impact of noise produced by wave energy devices on marine mammals using criteria based on audiograms of dolphins, or other species. The idea is to illustrate the application of that methodology, and to show to what extent it allows for estimating distances of impacts due to acoustic noise.

Keywords: Acoustic Modelling, Environmental Impact Assessment, Underwater Noise, Wave Energy Converters

Environmental Monitoring at the Maren Wave Power Test Site off the Island of Runde, Western Norway: Planning and Design

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Session IX, Thursday 13.00–14.05, Main hall

This paper provides a general description of the environmental monitoring programme currently

ongoing at Vattenfall's/Tussa's wave power test site "Maren", on the Norwegian west coast. The purpose of the environmental monitoring is twofold: (i) to monitor the potential impact of the Maren installation on the environment, thereby fulfilling the consent requirements of the Norwegian authorities, (ii) more generally, to gain experiences about the design and management of an environmental monitoring programme and test a variety of monitoring methodologies and equipment. The primary environmental parameters assessed in the monitoring programme include fish, benthos and seabird communities. Observations on marine mammals are included marginally and underwater noise measurements are scheduled to be included at a later stage. The rationale for choosing the specific components of the monitoring programme is elucidated in the context of site specific environmental features, as well as project-specific technical characteristics. Generally, the monitoring strategy follows a modified so-called BACI (Before-After, Control-Impact) design, i.e. takes place before and after deployment of the wave power devices and during operation over a period of approximately 3 years.

A communication plan accompanies the programme and is considered an essential prerequisite for transparency and public acceptance of the programme.

Keywords: environmental monitoring, wave power, test site, marine ecological communities, Maren

A 20 GW Thermal 300-metre³/sec Wave-energised, Surge-mode Nutrient-pump for Removing Atmospheric Carbon dioxide, Increasing Fish Stocks and Suppressing Hurricanes

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Session IX, Thursday 13.00–14.05, Main hall

As an outcome of a workshop following Hurricane Katrina this paper extends ideas submitted to the Royal Society Call for Submissions on geoengineering. The frequency and severity of hurricanes rise sharply if the surface temperature of the sea exceeds 26.5 C. This is because of our definition of hurricane categories rather than having anything to do with atmospheric physics. If we can pump warm water downwards to below the thermocline perhaps we can have gentle hurricanes. Designers of overtopping wave plant for energy generation want a high product of head and flow. But the head of water needed to overcome the density difference due to the temperature drop with depth in many hurricane breeding sites is often less than 200 mm. This means that we can use the horizontal movement of sea waves to move water through a wall of non-return valves into an enclosure with a down-tube reaching to the thermocline. The warm water from above will mix with cold, nutrient-rich water, giving a mixture of an intermediate temperature which will rise until it reaches the level of the same density, from where it will spread sideways. If this layer is at 100 metres below the surface there will be enough daylight to allow the growth of phytoplankton. These are efficient carbon absorbers and the start of the marine food chain.

Keywords: Climate change, wave-energy, nutrient pump, thermocline, hurricane suppression, phytoplankton, marine food chain

Modelling Tidal Energy Extraction in a Depth-Averaged Coastal Domain

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Session IX (second half), Thursday 14.20–15.25, Main hall

Numerical models have been used recently to quantify the effects of tidal extraction in specific tidal systems. Commonly, these studies have employed numerical approximations to the depth-averaged shallow water equations to simulate tidal hydrodynamics. Tidal power extraction has

then been introduced by incorporating an additional bed shear source term, or another general source term, to represent the presence of tidal devices.

We review these models and adopt an approach, based on actuator disc theory, to define the properties of a tidal device within a depth-averaged numerical model. This approach allows a direct link to be made between the actual tidal device and the equivalent momentum sink that the device should impart within a two dimensional (2D) depth-averaged domain. We use this description of a tidal device to model the hydrodynamic effects of energy extraction in an arbitrary coastal domain.

Keywords: actuator disc, resource assessment, shallow water equations, tidal power

Bridging the gap between biology (a rock) and physics (a hard place) for tidal energy research

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Session IX (second half), Thursday 14.20–15.25, Main hall

Marine turbine design and location may both influence the efficiency of the device and alter the potential for interaction with animals. The Isle of May is taken as a study site to investigate the utilisation of the water structure by the local marine community over the tidal cycle. Time dependant current profiles are quantitatively described (using ongoing data collection from an ADCP). Animal distribution and usage is explained using historic telemetry data and observation concurrent with oceanographic sampling.

Feeding hotspots are seen to occur in areas with particular oceanographic properties suggesting that foraging animals actively seek out certain environmental parameters. At the same time, it is thought that most marine animals use the dynamic nature of the water profile to enhance their foraging. In this way the distribution of actively foraging animals within the water column can be compared to the oceanographic properties and current regime to suggest optimal feeding conditions for the different species.

This information acts to highlight areas that would be unsuitable as sites for marine turbine location due to the increased risk of encounter with foraging animals. The 3-dimensional water column study is also used to advice device design in order to minimise the material and mechanical wear from oceanographic forcing.

Keywords: tidal energy, marine ecology, oceanography

European Marine Energy Centre: the development of a targeted environmental monitoring strategy and the streamlining of marine renewables consents in Scotland

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Session IX (second half), Thursday 14.20–15.25, Main hall

As the first facility of its kind anywhere in the world, EMEC provides wave and tidal developers with open-sea grid-connected testing facilities for single devices and small arrays. In addition to its technical and operational services, EMEC also provides in-depth assistance with all matters relating to the consenting of devices, which includes regular close liaison with regulators and stakeholders.

For devices being tested for the first time in the open sea, interactions with wildlife and other sea users need to be well understood. Primarily an operational test facility, there is also a

key role for EMEC to play in establishing and facilitating monitoring of devices regarding their potential impacts on the receiving environment and other sea users.

This paper presents an update on the environmental monitoring work underway at EMEC, together with work being undertaken by EMEC in the development of a Monitoring Strategy, which may be used as a basis for consistent monitoring by developers of individual units and small arrays of devices on test at the wave and tidal sites.

The paper also presents EMEC's work to streamline the consents process for the marine renewables industry in Scotland (under contract from Marine Scotland).

Keywords: Environmental impacts of wave and tidal energy devices, Marine energy environmental impacts, Marine energy environmental monitoring strategy

Numerical modelling of the response of tidal resonance to the presence of a barrage

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

A tidal energy barrage has been proposed for the Severn Estuary, UK. In order to predict the effect such a structure may have on the tidal resonance in the channel, a simple two dimensional model has been developed for a series of simulated estuaries, ranging from a simple box channel with a uniform flat bed to a simple wedge shaped channel with a solid barrier across, to a simulation of the Severn Estuary with topographic and bathymetric values. These models show amplitudes and phases of elevation and current flow for each model scenario. Model outputs show that overall tidal resonance decreases with the construction of a barrier across a channel.

Keywords: Resonance, tidal barrage, tidal energy

Topic 10

Policy development and legislation

Ocean Energy Systems Implementing Agreement: A New Collaborative Activity on Environmental Issues

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Session X, Tuesday 12.30–13.35, Main hall

The International Energy Agency's Ocean Energy Systems Implementing Agreement (OES-IA) is a working group of sixteen IEA member countries and the European Commission, which share a common interest in advancing ocean energy worldwide. Members of the OES-IA have been sharing efforts in 3 key areas:

- I) Review, Exchange and Dissemination of Information on Ocean Energy Systems,
- II) Development of Recommended Practices for Testing and Evaluating Ocean Energy Systems, and
- III) Integration of Ocean Energy Plants into Distribution and Transmission Electrical Grids.

In April 2009 the OES-IA launched a new collaborative task “*Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal, and Current Energy Systems*”.

This paper will present the various work programmes and publications of the OES-IA, present the current status of Ocean Energy technologies and barriers to technology penetration, thus contextualizing the relevance of the new task on Environmental Issues under the OES-IA work program.

Keywords: IEA, Implementing Agreements, Environmental Impacts, Marine Energy Converters

Review and discussion of common environmental legislation for ocean energy schemes

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Session X, Tuesday 12.30–13.35, Main hall

In Europe, there is a lack of appropriate legislation for environmental impact assessment specifically for ocean energy converter technologies. The review of the existing legislation at National level as well as the context of incoming European legislation can contribute to establish a common baseline for future environmental assessment legislation requirements in order to achieve

compliance within European countries. In this paper the legislative requirements for ocean energy schemes in some European countries is reviewed and compared with those established in other countries such as United States of America and Canada, two countries where the number of ocean energy projects is high. In addition, a comparison is also made with environmental legislation developed to accommodate other technologies, namely offshore wind energy, in order to highlight potential legal gaps.

Keywords: ocean energy, legislation review, environmental impact assessment, common baseline

Methodology for site selection for wave energy projects

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Session X, Tuesday 12.30–13.35, Main hall

Waveplam is a European project funded under the programme Intelligent Energy Europe, which aims at tackling non-technological barriers that may hinder the installation of wave energy projects and to speed up their introduction onto the European renewable energy market.

Inside *Waveplam*, one of the objectives is to generate recommendations for public or private promoters and investors to guide them through the process of planning and implementing a wave energy project.

The first task for achieving this objective consists of the development of a methodology for site selection. This paper introduces the methodology, which will try to help decision making through the definition of two stages. These stages relate to different levels of detail in the information promoters are going to require when planning installations at the sea.

In the first stage, gathering general information on the site will be necessary. The methodology will list the necessary information, as for example wave resource, availability of grid, proximity to end users, environmental protection areas and interference with other uses of the coast among others.

In the second stage further information gathering will begin. Ideally but not essentially, this will involve integrating the data as layers into a GIS (Geographic Information Systems) tool, given the spatial nature of the project. This tool will provide an accurate and convenient visual aid for choosing a suitable area.

Keywords: GIS, items of information, site selection, wave energy

Recent developments in wave energy along the coast of southern Africa

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Session XII (poster session), Tuesday 16.30–18.30, Main hall

The current status of wave energy development in southern Africa is presented by highlighting previous and more recent studies conducted on the wave power potential along the southern coast of Africa. These studies found a significant wave power resource that is evident by the interest of international developers of wave energy converters to deploy their devices along this coast. An updated version of the original Stellenbosch Wave Energy Converter, or SWEC, is

presented. This shore-based device will overcome some of the difficulties of the original SWEC and may become a technology demonstrator for a full-scale SWEC.

Keywords: wave energy development, wave power resource, wave energy conversion

Topic 11

Socio-economic impact

Stakeholder Perceptions of the Wave Hub Development in Cornwall, UK

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Session XI, Wednesday 10.50–11.55, Main hall

Despite a growing body of research examining stakeholder perceptions of offshore wind-farms, little social research has focused on offshore wave energy devices. With the Wave Hub project proposed for Hayle Bay, Cornwall, in 2010, it is apparent that even developments that are ‘out of sight, out of mind’ still require extensive stakeholder engagement if opposition is to be reduced. Findings from ongoing research into stakeholder perceptions of marine renewable energy suggest that the science underpinning these devices needs to be more robust and clearly articulated, with baseline data accounting for temporal shifts in marine environments, to allay stakeholder concerns. There also needs to be realistic information by project proponents on the local benefits of the Wave Hub project, as many stakeholders feel the public will be disappointed if benefits are artificially inflated. The Wave Hub also creates a quandary for some stakeholders who see supporting the Wave Hub as paving the way for widespread deployment of marine renewables, leading to significant impacts on marine environments. The more general findings from the study are that it cannot be assumed that ‘out of sight’ means ‘out of mind’ or that the same opposition factors identified for offshore wind developments apply to wave and tidal devices.

Keywords: Perceptions, renewable energy, stakeholders, Wave Hub

Ocean energy in combination with land-based renewable energy sources: appropriate technology for smaller electricity grids in Africa?

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Session XI, Wednesday 10.50–11.55, Main hall

The rapid development within ocean energy includes a numerous set of different energy converters differentiated both regarding technical scale and resource requirements. While many of the developers focus on resource hot-spots and commercialization in industrial countries, some

technologies may benefit from shifting into niche markets in developing countries. Prerequisites for future sustainable implementations of small-scale ocean energy for electrification of rural communities in low latitude developing regions are reviewed using African countries as case study. To meet the ubiquitous need of power generation at village level in remote areas renewable energy systems, often based on solar photovoltaic, are becoming more frequently implemented. Despite choice of energy source, several small rather than fewer large generators may be preferable since development of distribution grids is generally very slow. This paper discusses ocean energy converter concepts in the perspective of appropriate technology for developing country implementation, and its potential benefits of combination with other sources in small grids.

Keywords: Developing countries, renewable energy, small-scale, ocean energy, electrification

Economic Assessment of Marine Energy Schemes

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Session XI, Wednesday 10.50–11.55, Main hall

Although many marine energy technologies are presently being developed, only a small number of devices have generated electricity from the marine environment. From such a small experience base it is difficult to independently assess the economic feasibility of alternative technologies for large-scale electricity generation. With a few notable exceptions, much of the published work on marine energy costing concerns relatively small deployments (up to around 100 MW rated capacity) with a strong emphasis on costing the components of individual marine energy conversion devices. A review indicates that there is considerable variation of unit electricity cost estimates even for similar technologies. In part, this can be attributed to different end-user applications and input assumptions. Comparison between individual marine energy technologies is therefore not straightforward, particularly for non-technical groups such as potential investors or policy makers concerned with future electricity generation scenarios.

Informed by consultation with stakeholders and the 22 partners of the EU FP7 EQUIMAR project, we present a summary of alternative approaches used to evaluate the economic viability of a marine energy scheme. For several technology types, the main factors affecting the capital cost, operating cost and revenue associated with a commercial scale marine energy project are identified. To aid identification of high-risk cost areas, indicative quantities are assigned to the uncertainty and scale-dependence associated with several key inputs. This provides a framework for equitable assessment of diverse technologies.

Keywords: Economic Assessment, Uncertainty, Risk

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