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The effects of oblique waves and currents on the loadings and performance of tidal turbines

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ABSTRACT

Tidal energy exploitation is at an early deployment stage and costs need to be reduced to improve the long term economic viability of the sector. High costs of tidal turbines are, in part, the result of load uncertainties, which lead to the use of high factors of safety in the design to ensure survival. One of the most important causes of uncertainty is hydrodynamic loadings. To date, most of the scaled model experiments with horizontal axis turbines investigating this issue have been carried out with collinear wave and current directions. To the authors' knowledge, the work presented herein is the first experimental investigation of a horizontal axis turbine model subjected to combined oblique waves and current. Turbine performance and loading are measured for a 1:15 scale model tested in the FloWave circular, combined wave and current basin at the University of Edinburgh (UK). Three different flow directions were tested and each of them were also combined with regular waves in three different directions non-collinear with the flow. Fifteen physical quantities were measured including flow velocity, rotor and foundation loads and turbine speed. Characterisation of loads and turbine performance in those oblique current and wave conditions are presented. Waves affect means and standard deviation of rotor power and thrust, but off-axis waves are associated with lower thrust loads than head-on waves. Compared to current only, rotor torque and thrust standard deviations are higher in the presence of waves and almost twice as high when the wave crest is parallel to the rotor plan. The experimental data associated with this article can be downloaded from http://dx.doi.org/10.7488/ds/2360.

1. General introduction

Due to the ever greater urgency to address global warming issues, the Scottish Government (2013) has set a target of generating the equivalent of 100% of Scotland's electricity from renewable sources by 2020 with the added challenge of maintaining the country as a global lead in tidal and wave energy developments. Compared with other renewables such as wind and solar PV, tidal energy is at a relatively early stage on its maturity and needs continued research into fundamentals of machine loading and performance in realistic conditions to enhance reliability and cost effectiveness.

According to the Department of Energy and Climate Change (2013), the levelised cost of electricity (LCOE) from tidal stream sources is expected to reduce from 190£/MWh in 2025 to 171£/MWh by 2030 for shallow water deployments, and from 148£/MWh to 129£/MWh for deep water deployments. This is still not a competitive generation method compared to onshore wind turbines over 5 MW per unit which is forecasted to have in 2030 a LCOE of 97£/MWh. This is due to the high cost of capital expenditure (CapEx) and operational expenditure (OpEx). A solution to lower the LCOE is to reduce CapEx by optimising the structural design of the device whilst maintaining the device's performance and survivability. A possible approach is to lower the factors of safety (FS) that account for the design and performance uncertainties arising from loads in naturally occurring flows. A way to assess the effect of these loads is physical testing of scale models.

There is an extensive literature on tidal turbine testing based upon physical models. Bahaj et al. (2007) used a 0.8m rotor in a towing tank, finding that the highest performance for their tidal turbine model was at a tip-speed ratio (TSR) $\lambda = 5$–7 with pitch angle of 20°. They found that the power coefficient (C_P) of the turbine decreases as the rotor is yawed and when the turbine tip is around 0.19D from the water surface. Mycek et al. (2014), with a 0.7m rotor, Gaurier et al. (2013) with a 0.9m rotor and de Jesus Henriques et al. (2014) with a 0.5m rotor, all in a recirculating tank, observed that wave-induced fatigue loads show a standard deviation two to three times higher than for the current-only induced fatigue loads and represents a significant risk of failure. The average C_P and the average thrust coefficient (C_T) are however not affected. In addition, they found that the ambient turbulence affects the

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fatigue loadings on the turbine, but not its performance. At higher turbulence intensity (TI), the wake was observed to recover faster than at lower TI. Luznik et al. (2013) with a 0.46m rotor tested in a towing tank, observed that in the absence of waves the turbine can operate at lower TSR values.

Evans (2014) and Easton (2013), using ADCP measurements at Ramsey Sound (Pembrokeshire, Wales, UK) and the Inner Sound (Pentland Firth, Scotland, UK) respectively, showed that the main flow direction at potential tidal sites can vary by up to 20° between flood and ebb. Their findings were used to inform the range of directionalities explored in the present work. In the field, although there is a predominant wave direction, there will be occasions when the wave direction varies from this. The wave direction is independent of the tidal flow direction. To the authors' knowledge however, the influence of waves not collinear to the current has not been explored in the literature, perhaps in part due to the limited number of testing facilities capable of producing such conditions.

The turbine model used for this project is described in Payne et al. (2017). The article details the design process of the turbine. Blade Element Momentum (BEM) is first used estimate the loads the turbine would be subjected to, which in turn informs the specifications for the force sensors and for the drive train. Finite Element Analysis (FEA) is used to ensure that the blades can structurally withstand the loads. Preliminary results from testing carried out in the recirculating flume of IFREMER in Boulogne-sur-Mer, France is also presented including C_P and C_T curves, load time series and wake measurements.

The tests for this project were carried out in the FloWave basin of the University of Edinburgh whose characteristics have been documented in Noble et al. (2015) and Sutherland et al. (2017). Both articles describe a fairly straight velocity depth profile from the surface up to mid-depth with slower speeds closer to the bottom of the basin. They observed that at 1.5m above the floor, the measured flow speed experiences significant spatial variation throughout the basin's raiseable floor area and it can be up to 50% lower than the prescribed value. The velocity depth profiles change considerably as the flow measurements are performed further away from the basin's centre, especially on the transverse direction to the flow. Significant changes become noticeable outside a ~5 meters radius. Noble et al. (2015) propose a working area of 8-by-6 meters outside of which the spatial variations are of the order of 10% of the nominal speeds. Inside this working area, all speed measurements are within 5% of the nominal speed.

The main objective of this study is to identify the effects of oblique waves and currents on the root bending moment of the blades, on the rotor thrust and torque loadings and on the performance of a tidal turbine. Presently, the use of Factors of Safety (FS) protect the devices from damage due to uncertain flow characteristics, the aim of this work is to reduce these design uncertainties. Tests were undertaken in a circular tank that allows the generation of waves and currents at any desired angle. This research used a 1.2 m diameter horizontal axis turbine model and a matrix of wave and current parameters ranging from collinear to oblique interactions. This work expands the findings from Martinez et al. (2017).

This work is divided in two main sections: flow characterisation and turbine testing. These sections are preceded by a general introduction of the testing facility and turbine model.

2. The experimental facility and turbine model

2.1. Wave-current basin and instrumentation

The FloWave facility, shown in Fig. 1, is located at The University of Edinburgh in Scotland, UK. It is a 25m diameter circular basin with a 2m working depth and a 15m diameter elevating floor to facilitate access to the basin bottom when setting up models. Current is generated by 28 5-bladed, 1.7m diameter impellers arranged around the full circumference of the basin. Multidirectional wave generation is archived by 168 absorbing flap type wavemakers, also arranged around the full circumference. This facility has the advantage of creating flow and waves independently at any given angle (Robinson et al., 2015). It was specifically designed to support tidal and wave energy research and development in intermediate water depths.

An Acoustic Doppler Velocimeter (ADV) was used for all flow measurements. The specific instruments used was a Vectrino Profiler from Nortek. This instrument can measure flow velocities up to 3.0 m/s at a sample rate of up to 100Hz.

Wave elevation are measured using resistive wave gauges. These are sampled at 64Hz and were calibrated every day before testing.

2.2. Turbine model

The turbine model used for the tests was designed and built by Payne et al. (2017) at the University of Edinburgh under The Engineering and Physical Sciences Research Council (EPSRC) funded project “X-MED” (EP/J010235/1). It consists of a 1:15 scale, 1.2m diameter rotor that represents an 18m diameter turbine at full scale. The blade profile is a NACA 63-8XX made of aluminium, manufactured by computer numerical control (CNC) machining. For these experiments, the turbine was operated under speed control. Fig. 2 shows the turbine mounted on the basin floor. All the instrumentation is kept protected inside the black and silver cylindrical sleeves.

The turbine was first tested at IFREMER in Boulogne-sur-Mer, France with results presented by Payne et al. (2017).

2.2.1. Turbine instrumentation

The turbine model is fitted with a transducer measuring rotor torque and thrust on the rotor only. It also includes sensors measuring the stream-wise root bending moment at the root of each blade. A resolver records the absolute angular position of the rotor. All the turbine sensors are sampled synchronously at 256Hz. The root bending moment load cells developed a fault during the tests and their measurements are therefore not analysed herein.

3. Flow characterisation

3.1. Introduction and methodology

In order to understand the onset flow the turbine was going to be exposed to, a campaign of flow characterisation tests was carried out before putting the turbine in the water. This section describes the tested conditions and findings.

Fig. 3 shows a top view of the basin, with a blue marker representing the location of the turbine. The dashed lines represent the wave angles selected and the solid, coloured lines, represent the flow angles. A flow speed of 0.8 m/s was selected. This is the design speed for the turbine model presented by Payne et al. (2017). From Froude scaling, this corresponds to a full-scale velocity of 3.1 m/s which, according to McNaughton et al. (2015), is a realistic flow speed for deployment sites such as the European Marine Energy Centre (EMEC). The wave directions were chosen to provide a broad range of conditions within the testing time allocated and the technical capability of the facility. In that context, tests in 180° opposing wave were not carried out as it limits the range of wave period available (because of the Doppler effect). 90° waves were also excluded because the associated wave induced velocity will be parallel to the rotor disc and will therefore have limited influence on its load. Wave heights and periods were chosen to produce (according to linear wave theory) a horizontal wave induced velocity at hub height of 0.1 m/s. Such a flow speed fluctuation is within the capability of the turbine model and would be associated at full scale with a 1.5m wave height and 8s wave period.

Wave heights and periods were selected to generate a wave-induced horizontal water particle velocity at hub height of 0.1 m/s. Three regular waves were used with the characteristics shown in Table 1.