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Quantifying wave and yaw effects on a scale tidal stream turbine

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The behaviour of Tidal Stream Turbines (TST) in the dynamic flow field caused by waves and rotor misalignment to the incoming flow (yaw) is currently unclear. The dynamic loading applied to the turbine could drive the structural design of the power capture and support subsystems, device size and its proximity to the water surface and sea bed. In addition, the strongly bi-directional nature of the flow encountered at many tidal energy sites may lead to devices omitting yaw drives; accepting the additional dynamic loading associated with rotor misalignment and reduced power production in return for a reduction in device capital cost. Therefore it is imperative to quantify potential unsteady rotor loads so that the TST device design accommodates the inflow conditions and avoids an unacceptable increase in maintenance action or, more seriously, suffers sudden structural failure.

The experiments presented in this paper were conducted using a 1:20th scale 3-bladed horizontal axis TST at a large towing tank facility. The turbine had the capability to measure rotor thrust and torque whilst one blade was instrumented to acquire blade root strain, azimuthal position and rotational speed all at high frequency. The maximum out-of-plane bending moment was found to be as much as 9.5 times the in-plane bending moment. A maximum loading range of 175% of the median out-of-plane bending moment and 100% of the median in-plane bending moment was observed for a turbine test case with zero rotor yaw, scaled wave height of 2 m and intrinsic wave period of 12.8 s.

A new tidal turbine-specific Blade-Element Momentum (BEM) numerical model has been developed to account for wave motion and yawed flow effects. This model includes a new dynamic inflow correction which is shown to be in close agreement with the measured experimental loads. The gravitational component was significant to the experimental in-plane blade bending moment and was also included in the BEM model. Steady loading on an individual blade at positive yaw angles was found to be negligible in comparison to wave loading (for the range of experiments conducted), but becomes important for the turbine rotor as a whole, reducing power capture and rotor thrust. The inclusion of steady yaw effects (using the often-applied skewed axial inflow correction) in a BEM model should be neglected when waves are present or will result in poor load prediction reflected by increased loading amplitude in the 1P (once per revolution) phase.

1. Introduction

Tidal Stream Turbine (TST) technology is currently at the prototype stage where unique devices are being deployed at specific sites or marine energy testing centres. The United Kingdom, United States, Canada and South Korea amongst others have been at the forefront of the evolution of freestream tidal energy technology. In many parts of the world freestream tidal energy presents a lucrative resource; estimates for the UK is that the technically extractable resource is 18 TWh/year [1] whilst in North America 1.6 TWh/year has been estimated from 7 specific locations [2]. South Korea has a number of locations on the south coast where it has been projected that several hundred MW of installed capacity could be deployed in order to reduce the country's reliance upon energy imports [3]. Historically there has been incidental data regarding flow velocities at sites with strong tidal flows often only stating spring peak and neap velocities for shipping and navigational purposes. With the advent of TST technology high quality data sets with increased temporal and spatial resolution are slowly being acquired at locations where technology is either installed or planned for deployment. Existing equipment (primarily Acoustic Doppler Current Profilers or ADCPs) used to measure tidal currents employs divergent acoustic beams in order to measure flow speed and direction

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vertically through the water column, often with the added capability to measure water surface elevation to determine characteristics of waves. Whilst binned data through the water column is advantageous, device geometry and principals of operation mean that standard deviation of acquired data over very short time intervals is significant, requiring time-averaging. In addition the measurement volumes (especially far from the instrument) are large. This means that short timescale effects cannot be accurately quantified (due to data averaging) and eddies and turbulence are poorly quantified although efforts have been made to correlate divergent and convergent acoustic instruments to provide better estimates of higher-order flow effects such as turbulence intensity [4]. Research carried out at the European Marine Energy Centre showed that in a water depth of 45 m, the orbital motion of the waves penetrated as far down as 20 m whilst a region of sheared turbulent flow propagated vertically upwards from the sea bed. This resulted in approximately the middle third of the water column remaining relatively stable [5]. The results from a single site cannot be considered general; however it is clear that the need for better understanding of the flow field at tidal energy extraction sites is vital for quantifying device loads and optimising energy capture from larger diameter rotors. Accurate quantification of higher-order flow effects and characterisation of turbulent length scales would prove a great benefit to the technology.

The effect that short-duration and length-scale flow features will have on TSTs is unclear, which will undoubtedly lead to prototype devices being over-engineered and installed at sheltered locations where such effects are minimised [6]. The state of the industry to date has predominantly seen deployment at relatively sheltered sites. MCT [7] have installed their TST in a loch in Ireland, Hammerfest Strom [8] in a fjord in Norway, Open Hydro [9] at the EMEC [10] test facility in Scotland and Scottish Power Renewables [11] have recently received consent for an array off the isle of Islay in a fjord protected from the Atlantic. The use of such sheltered sites is wise in the early stages of the technology where reliability and operability are key issues. However, the largest resource often lies at locations exposed to waves or with strong turbulent flow features due to varying bathymetry or eddies shed from land masses. Bearing in mind that TSTs of a given rated power typically experience four times the thrust of a wind turbine of the same rated power the need to quantitatively assess the dynamic blade loading under such unsteady flow conditions is essential if the technology is to move into the most energetic waters. At present, few experimental wave–current studies have been conducted in the presence of TSTs. One particular study combined Blade-Element Momentum (BEM) theory and linear wave theory to predict rotor torque and thrust and to assess the influence of waves on the dynamic properties of bending moments at the root of rotor blades [12]. The outcomes were limited, particularly those for the blade loading. This paper includes studies into yawed and dynamic load effects on a model turbine rotor and blades.

2. Methodologies

2.1. Wave-towing tank experiment

The experiments presented in this paper were conducted in a wave-towing tank (60 m long × 3.7 m wide × 1.8 m deep). A 1:20th scale tidal turbine with rotor diameter 0.8 m (Fig. 1a and Fig. 2b) was equipped with the capability to measure rotor thrust and torque utilising a custom waterproof dynamometer. This was installed ahead of any seals and bearings to increase accuracy. The design of the dynamometer was discussed previously [13] and was based on the extensive work carried out by Molland [14] for their research on ship propellers. Rotor velocity and acceleration was measured using a hollow shaft encoder mounted within the turbine nacelle. The encoder also provided precise azimuthal position for a strain gauged turbine blade measuring out-of-plane and in-plane root bending moments. A wireless telemetry system located inside the turbine nacelle collected filtered and amplified signals from the strain gauges before data was conveyed above the waterline via a sealed umbilical cable. All data was acquired simultaneously during each run on the towing carriage. The parameters varied included: Tip-Speed-Ratio (TSR), rotor yaw angle, characteristics of monochromatic waves and turbine proximity to the water surface. The blades utilised a NACA 48XX profile with varying thickness and twist along the chord length.

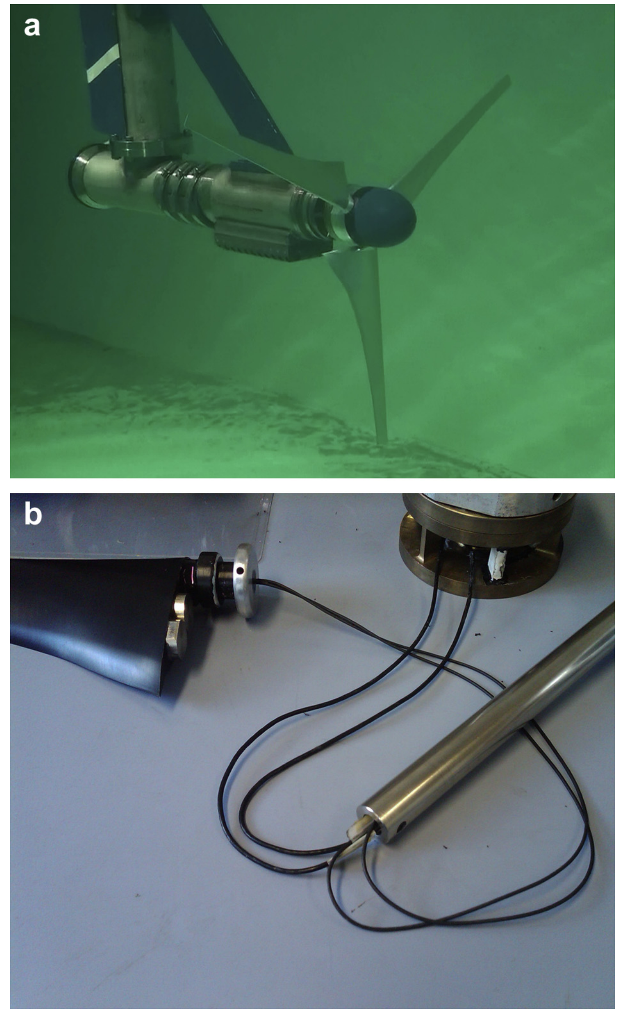

Fig. 1. a – Underwater photo of 1:20th-scale tidal turbine model with NACA 48XX blades. 1b – Strain gauged blade root and dynamometer wires feeding into shaft.

The model turbine was a Froude scaled representation of a 16 m diameter TST. Water waves are gravity dominated and since waves were used throughout the experiments, Froude scaling was the dominant scaling parameter. The fact that the yaw effect may be Reynolds number dominated is simply unfortunate in this case. The towing speed was kept constant at 0.9 ms^{-1}. This is equivalent to a full-scale uniform current speed of 4 ms^{-1}, which is significant for a suitable TST location; however it is significantly lower than the maximum current speed of 8.55 ms^{-1} used in the experiments conducted by Barltrop [11]. High velocities tend to be used in tidal turbine experiments because a low