Experimental and numerical results of rotor power and thrust of a tidal turbine operating at yaw and in waves

Pascal W. Galloway[1,*], Luke E. Myers[1], AbuBakr S. Bahaj[1]

[1] *Sustainable Energy Research Group, School of Civil Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, UK.*
**Corresponding Author Tel +44(0)23 80595458, E-mail: P.W.Galloway@soton.ac.uk*

Abstract: Little has been done to investigate the behaviour of Marine Current Energy Converters (MCECs) in unsteady flow caused by wave motion and yaw. The additional loading applied to the rotor through the action of waves and whilst operating at yaw could dictate the structural design of blades as well as the proximity to the water surface. The strongly bi-directional nature of the flow encountered at many tidal energy sites may lead to devices employing zero rotor yaw control. Subsequent reductions in device capital cost may outweigh reduced power production and increased dynamic loading for a rotor operating at yaw. The experiments presented in this paper were conducted using a 1/20th scale 3-bladed horizontal axis MCEC at a large towing tank facility. The turbine had the capability to measure thrust and torque via a custom waterproof dynamometer. A BEM (Blade Element Momentum) code developed within the university was modified to include wave and yaw, with a view to further understanding the primary loading upon the rotor and individual blades.

Keywords: *marine current energy converter, wave-current interaction, strain gauge, loading*

1. Introduction

One of the enduring topics of interest in the field of coastal and offshore engineering is that of wave-current interactions and their effect on static and dynamic structures. The co-existence of waves and currents is a common feature in the marine environment [1]. Waves are strained and refracted by currents, causing exchanges of mass, momentum and energy to occur between the waves and mean flow [2]. The main energy in the coastal region can be attributed to tides, surges and wind waves. Interactions occur between these different 'waves' because the tides and surges change the mean water depth and current field experienced by the waves [3]. The usual approach to the interaction problem has been to ignore the interaction between waves and currents and simply add the two together (using their particle velocity vectors) so as to calculate the forces on a body [4].

Marine Current Energy Converter (MCEC) technology is currently at the prototype stage where unique devices are being deployed at specific sites or marine energy testing centers. There is little detailed knowledge of the flow field properties at highly energetic tidal energy sites [5]. Generally peak flow speeds are measured but the effect of wave and bed generated turbulence is neglected. The effect this will have on MCECs is unclear, which may lead to prototype devices being installed at sheltered locations where these effects are minimised [5]. If this becomes a trend with developers it may result in reduced energy capture as blade diameters are constrained and potentially higher energy flows are not utilised. MCECs of a given rated power typically experience four times the thrust of a wind turbine of the same rated power, even though the MCEC will be significantly smaller in diameter. Thus it is expected that rotor loading and general structural integrity could be significant for MCEC devices. Therefore the need to quantitatively assess the blade/rotor loading caused by wave-current interaction is clear. At present, few experimental wave-current studies have been conducted in the presence of MCECs. One particular study combined Blade Element Momentum (BEM) theory for wind turbines 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 [6]. The outcomes were limited, particularly those for the blade loading. In the field, research carried out at the European Marine Energy Centre showed that in a water depth of 45m, wave effects penetrated as far down as 15m whilst turbulence from the bottom boundary layer penetrated up as much as 17m. This resulted in approximately a third of the water column remaining relatively tranquil [7]. If blade loading in the more turbulent regions could be quantified then this may allow for greater energy capture from larger diameter rotors.

2. Methodology

2.1. Towing Tank Experiment

The experiments presented in this paper were conducted in a wave/towing tank (60m long x 3.7m wide x 1.8m deep). A 1/20th - scale tidal turbine model (see Fig.1) was equipped with the capability to measure rotor thrust and torque (utilising a waterproof dynamometer) and rate of rotation (via optical sensors). The parameters varied included: TSR (tip-speed-ratio), turbine yaw and turbine submergence depth. The blades utilised a NACA 48XX profile with varying thickness and twist along the chord length. The waves used had a height of 0.1m and a 1.34s intrinsic period; current speed was 0.9ms^{-1}.

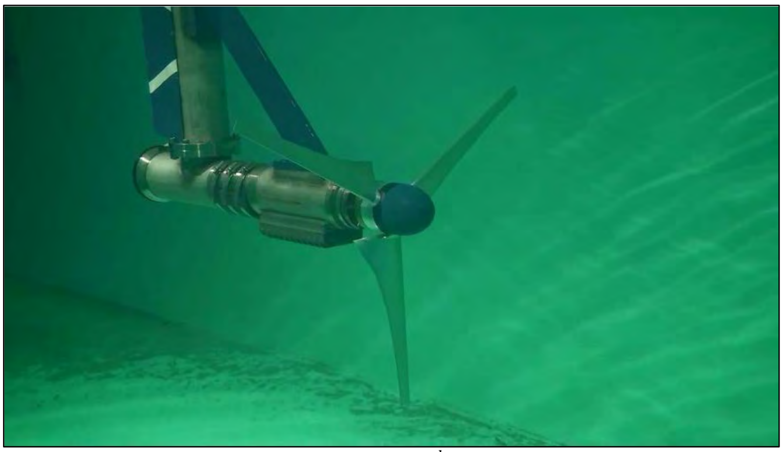

Fig. 1. Underwater photo of 1/20th scale tidal turbine model

The design of the thrust-torque dynamometer utilised for this work is discussed previously [8] and was based on the extensive work carried out by Molland and Turnock [9] for their research on ship propellers. 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. The model turbine is a Froude scaled representation of a 16m diameter MCEC. The maximum scaled current speed would be 4m/s, which is significant for a suitable MCEC location; however it is significantly lower than the maximum current speed of 8.55m/s used in the experiments conducted by Barltrop [6]. High velocities tend to be used in turbine experiments because a low Reynolds number can degrade the dynamical properties of the airfoil and can be a source of irregularity between the experimental data and simulation data [6]. Laboratory experiments are useful for approximating these wave-current phenomena since little detailed knowledge exists for tidal energy sites since there has never before been the need for such data [5]. The problem is that the use of a towing tank results in no actual Doppler shift in the waves because there is no real current present (see section 2.2). More complex facilities such as a circulating water channel with wave-making facilities would be more representative; however depths would need to be at least 2m with the ability to generate waves from a range of directions relative to the current.

2.2. Numerical Model

Numerical modelling has shown that the influence of waves complicates the flow with its influence being more than just adding turbulence. The dynamic part of the waves causes significant oscillations in the power and thrust, which in-turn influence the 'quality' of the electrical power production. High frequency oscillations (known as flicker) occur. It is thought that this flicker is caused by variations of the angle of attack under the influence of wave motion [10]. The nature of wave-current interaction is complex: If a current encounters a wave in the same flow direction, the wave height decreases with an increase in wavelength, whilst the current speed increases. The opposite is true if the current encounters a wave in the opposite flow direction [3].

A Doppler shift is observed when surface waves and current velocities interact. The primary effect of a current is to change the frequency of the waves due to a Doppler shift. The observed angular frequency, ω, of the ωaves in a frame of reference moving ωith the current, σ, the intrinsic angular frequency and the wave number, k, is given by:

$$\omega = \sigma + kU \quad (1)$$

This relationship describes how the observed wave frequency reduces or increases based on current velocity. A Doppler shift is valid in the case of a constant current, but a more complex effect is noted in the case of sheared currents. Use of linear wave theory superimposed on a uniform current does not give a strictly accurate representation of wave-current interaction effects. It is however a straightforward approach and may yield adequate results for a MCEC. Linear wave theory has been found to be a f airly accurate representation of wave-current interaction in depths of water greater than 12.5m and with significant wave heights lower than 5m for the purposes of dispersion [3].

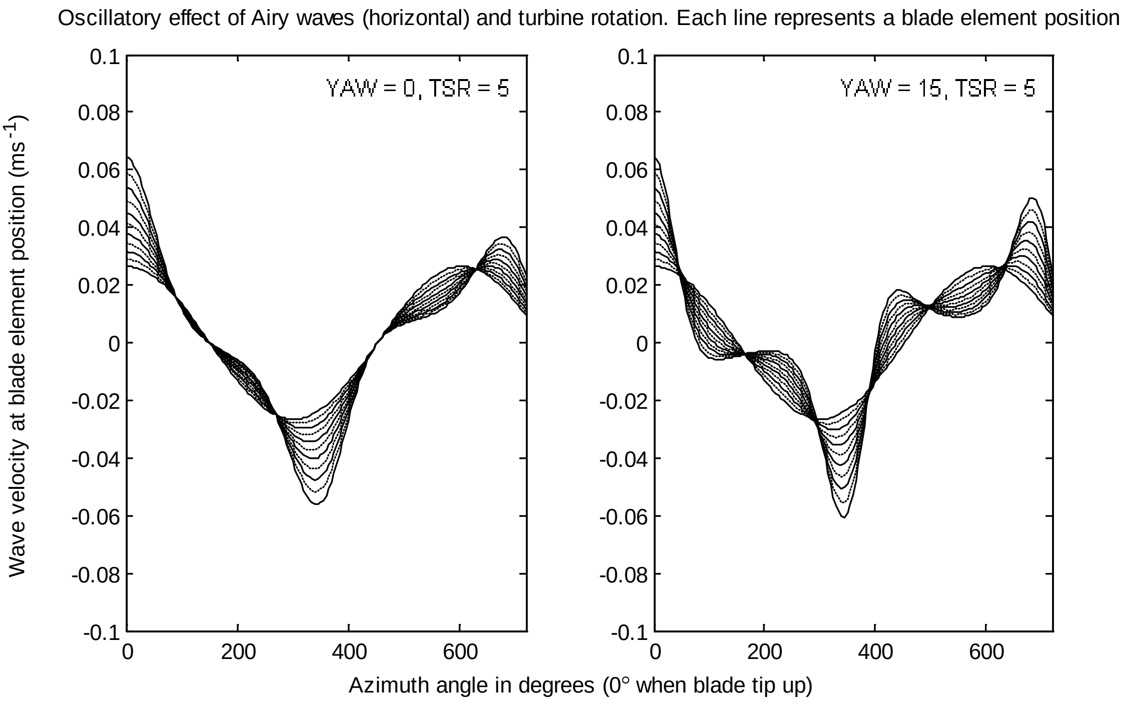

Fig. 2. 1st order wave-current interaction velocities as seen at individual blade elements over two revolutions. The left figure is for zero yaw, the right figure is for 15° yaw. The largest oscillations can be observed at the outer element i.e. at X=1, the tip of the blade (X = elemental radius/blade radius)

It is well known that BEM theory is commonly used by wind turbine designers for predicting loads and power outputs for wind turbines. Although this theory is readily applicable to MCECs there are some differences. Wind for example does not have a characteristic property that resembles wave-current interaction; therefore this must be taken into account when designing prototype MCECs. A BEM code has been modified to include the effect of monochromatic waves on a uniform current with the inclusion of yawed flow if desired. The model assumes that there is no distortion to the incoming flow field or lateral velocity variation and that rotor speed is constant. An example of the wave velocities observed at a single blade can be seen in Fig.2. These velocities are calculated using linear wave theory with a D oppler shift. Based on BEM geometry, these velocities are then calculated instantaneously at each blade element for a given TSR and yaw angle. This output then feeds directly into the BEM code (see Fig.3 for an outline of the numerical model).

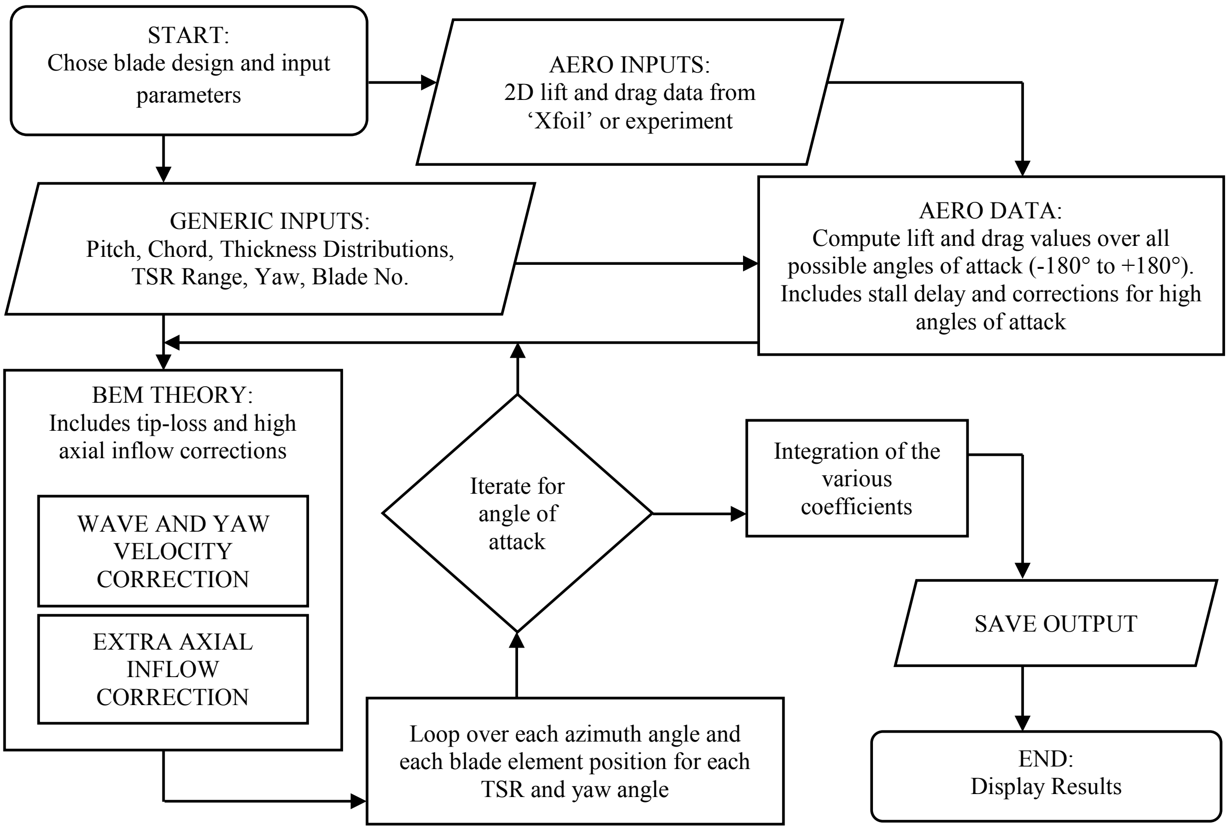

Fig. 3. Flow diagram for BEM numerical model showing the processes involved

3. Results and Discussion

The model MCEC (Fig.1) was used to acquire measurements of thrust, torque and rotor speed for both yawed and wave environments. Fig.4 shows the comparison between experimental data and numerical model for a yawed and un-yawed case. Blockage corrections by Barnsley and Wellicome [11] have been applied to the data. This is a requirement since measurements tend to be over predicted in relatively narrow channels (blockage is ~7%). Figures 5-8 are for a NACA 63-8XX blade, used for comparison with Bahaj et al. [12]. Results show good agreement, which when viewed alongside Fig.4, gives some confidence that the numerical model is valid. No figure is included to show the effect of waves on mean C_P and C_T because the resulting mean wave velocity at the rotor is approximately zero.

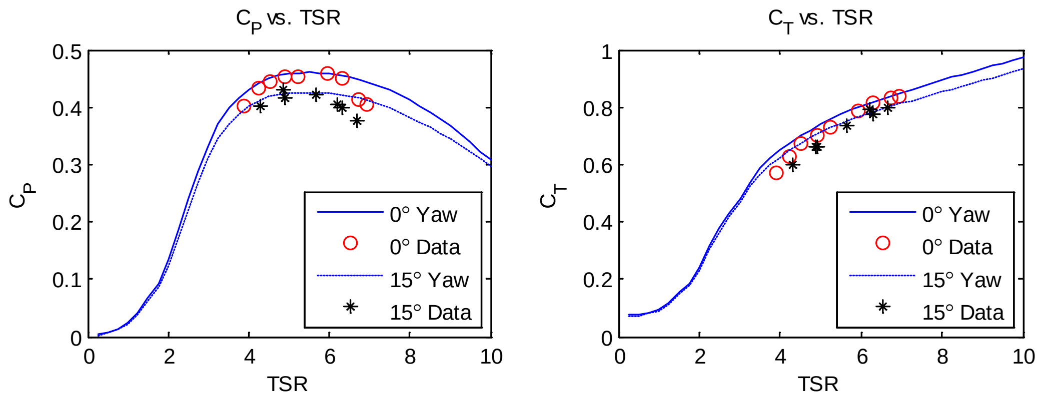

Fig. 4. Left: Power coefficient (CP) vs. TSR for 0° yaw and 15° yaw with experimental data included for comparison. Right: Thrust coefficient (CT) vs. TSR for respective yaw angles

The effect of waves is pronounced when investigating the azimuthal variation of C_P and C_T however, and has serious implications for the fatigue loading of blades as shown in Figures 5 and 6. A few of the parameters used in BEM are shown in these figures and the range over which they vary is represented by the plot line thickness. In Fig.5, the gradient of C_P is calculated using several of the other variables shown in the figure, amongst others. At zero gradient, C_{P_MAX} occurs at 85% blade radius, which is also the region of maximum power variation. This model assumes constant rotor speed which is unlikely to occur in reality. The variations seen in the angle of attack are likely to cause acceleration and deceleration of the rotor which may lead to a greater range of C_P.

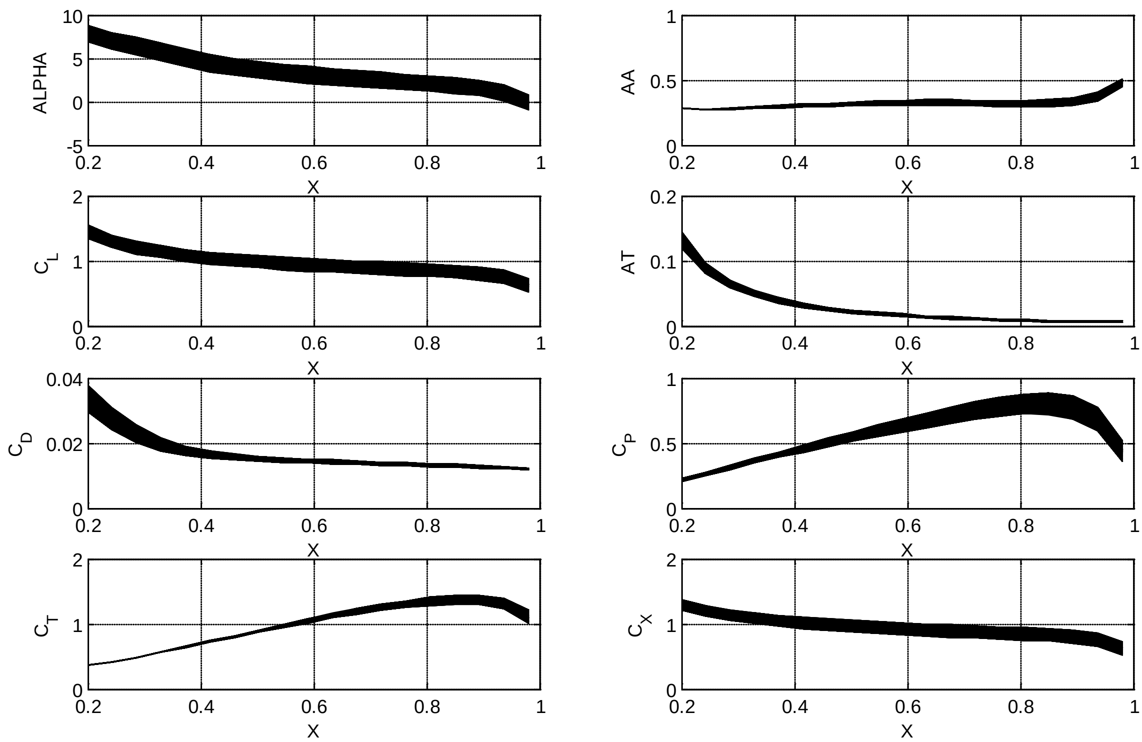

Fig. 4. Plots showing change in Alpha (angle of attack), C_L (lift coeff'), C_D (drag coeff'), AA (axial inflow factor), AT (tangential inflow factor), C_P (power coeff'), C_T (thrust coeff'), C_X (axial force coeff') across the blade span. Line thickness in each plot shows the effect of azimuthal variation. Only small waves are shown here. TSR = 6, Yaw = 0°

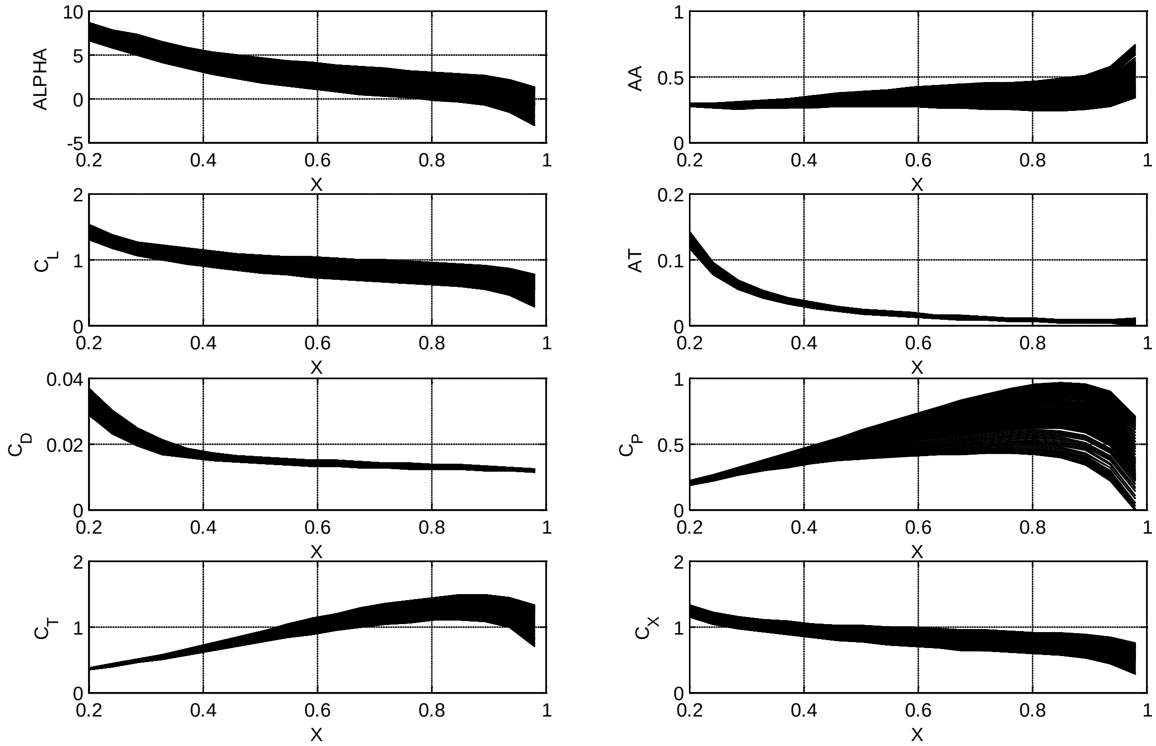

Fig. 5. See Fig.5 for description. Small waves and 15° yaw are shown here. TSR = 6, Yaw = 15°

This vindicates the concerns of flicker due to varying angle of attack (see section 2.2); since high frequency oscillations in voltage, caused by rapid changes in rotor speed, can lead to flicker in the power.

When a turbine is yawed to the flow, both power and thrust are reduced (see Fig.4). This is only apparent above 7.5° yaw with an approximate 20% power reduction at 22.5° yaw [8]. This is a noticeable difference and is likely to be higher than the 20% suggested because the rotor experiences a reduced effective velocity in yawed flow, hence reduced TSR.

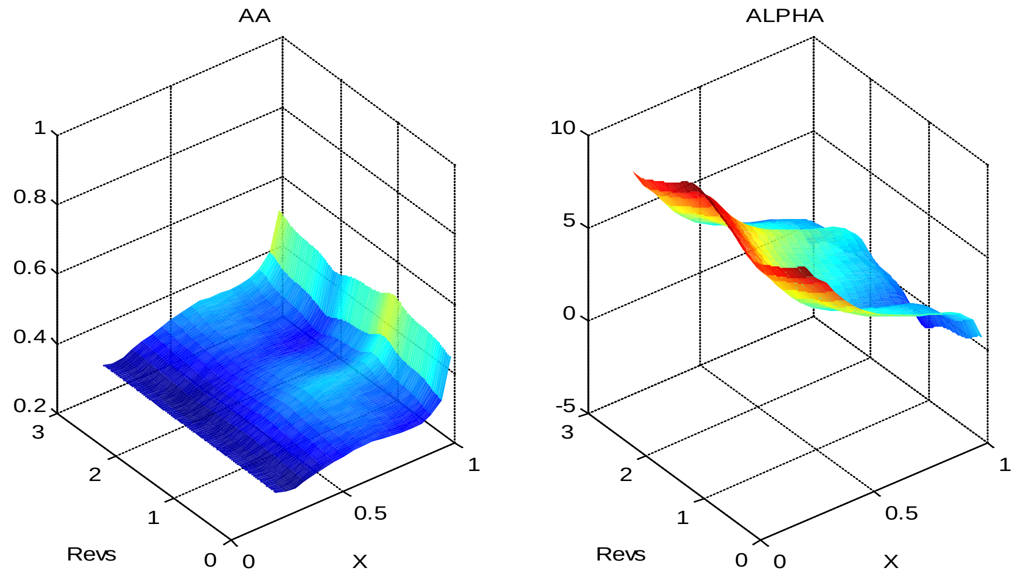

Fig. 6. Surface plots showing axial inflow factor and angle of attack from Fig.5 varying with blade radius and azimuth (3 revolutions)

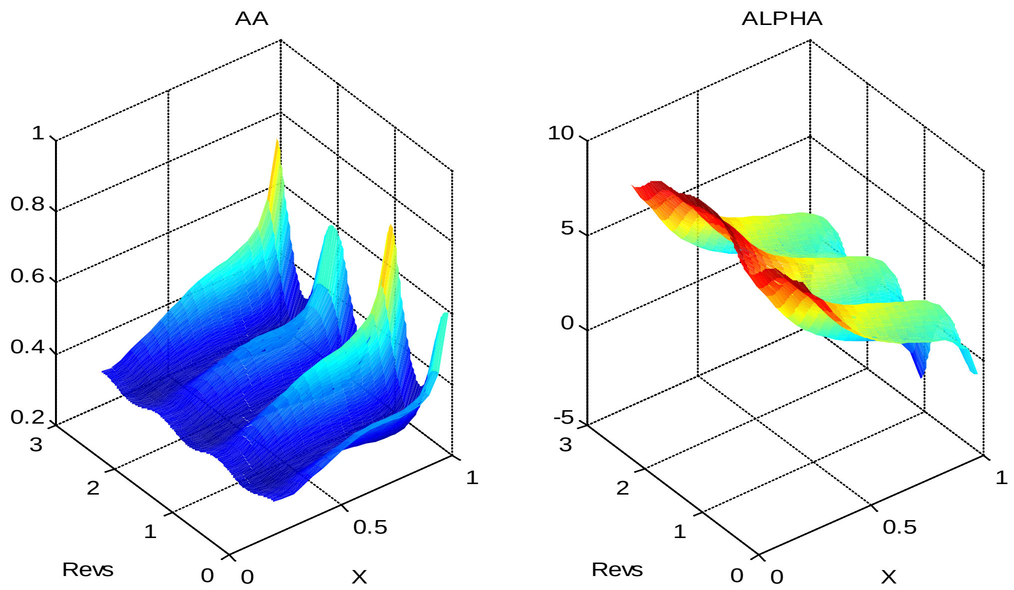

Fig. 7. Surface plots showing axial inflow factor and angle of attack from Fig.6 varying with blade radius and azimuth (3 revolutions)

The inclusion of yaw dramatically increases the range over which some of the parameters vary (see Fig.6). CP in particular varies ~3 times more at 85% blade radius for 15° of yaw. Surface plots in Figures 7 and 8 have been included to show how the axial inflow factor and the angle of attack vary over 3 blade revolutions, with and without yaw (15°). It should be noted that in Fig.8, the waves have less influence than yaw in the power producing region of the blade. This is an important point because the yaw effect can easily be avoided with the use of a yaw drive.

4. Further Work

This research is ongoing and further work will include more detailed experiments including additional testing at yaw into waves and measurement of individual blade loading. When the effects of linear theory have been properly evaluated, the next phase of testing will be to verify findings using waves on a non-uniform current. Barltrop [6] showed that the bending moments at roots of MCEC blades were found to fluctuate significantly; 50% of the mean value for out-of-plane bending moments and 100% of the mean value for in-plane bending moments. This justifies the need for individual blade loading experiments. In addition, steeper waves were found to impose lower bending moments in both directions about the roots of the rotor blade. It should also be noted that the in-plane bending moment is affected by the gravity bending moment component, so a neutrally buoyant blade would be desirable, if not impractical for a small model.

The BEM code will be expanded to describe the loading effects on a turbine blade in more detail. Further work will include modelling of blade acceleration, gravity effects and added mass, with a view to providing a model for fatigue analysis. This model could then be used for the design of optimised MCEC blades for tidal environments.

5. Conclusions

It has been demonstrated that waves are likely to have a detrimental impact on MCECs. This is not a significant problem in terms of power output, other than to further complicate the power electronics required for smoothing the power/flicker. The main issue with wave-current interaction around a MCEC is the cyclic loading, which will likely result in accelerated fatigue to the rotor and blades. This is particularly evident in the axial flow direction. Another important consideration is whether a rotor yaw drive is required at any specific tidal site. Large amounts of directional swing will occur around headlands and can cause a significant reduction in power and increase in dynamic loading if a yaw drive is omitted. The continuing work presented in this paper will eventually assist in the structural design of MCEC rotor blades, quantify the loading effects caused by waves and maximise rotor diameter to achieve a robust, high energy yield device.

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