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Wake studies of a 1/30th scale horizontal axis marine current turbine

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Abstract

A 0.4 m diameter (1:30th scale) horizontal axis marine current turbine (MCT) was tested in a circulating water channel. The turbine performance and wake characteristics were determined over a range of flow speeds and rotor thrust coefficients. Measurements of the water surface elevation profiles indicated increasing variation and surface turbulence with increasing flow speeds. Blockage-type effects (where the measured point velocity was greater than the inflow velocity) occurred around the sides of the rotor for all flow speeds. Although the effects were exaggerated at model scale, it is expected that reasonable variations in water level and flow velocity could also occur over a full scale MCT array.

Keywords: Marine current turbine; Wake; Array; Blockage; Flow

1. Introduction

The utilisation of marine currents for power production offers a sustainable option to augment traditional power technologies and enhance the expansion of renewables (Bahaj and Myers, 2003). The marine current resource is potentially large and could generate a significant fraction of the UK's electricity requirements. Energy from marine currents is highly predictable making it an attractive option amongst other renewable technologies. The main aspect of this work was the study of flow effects for a 1:30th scale horizontal axis marine current turbine (MCT) with particular regard to wake velocities and water surface profiles. The former is important to ascertain the longitudinal spacing of devices in a large array or farm. Water surface profiles (both up and downstream) are expected to be affected when MCT devices are extracting energy from a flow (Bryden et al., 2004). Changes in water surface elevation may affect the clearance between rotor blades and the surface leading to a reduction in MCT performance and increased wear due to cyclic loading. Rotors could also be strategically placed creating regions of high velocity flow (Fraenkel, 2002). To date little work has been done to address the problems faced in this area despite the fact that small MCT arrays of farms may be installed before 2010.

2. Experimental parameters

The model MCT was tested in a Circulating Water Channel (CWC) at the Qinetiq naval research facility, Gosport, Hampshire. Fig. 1 shows the model in operation. The CWC has a maximum flow speed of around 4 $\mathrm{ms^{-1}}$, maximum water depth of 0.84 m, width 1.4 m and working channel length of approximately 4.4 m. The model MCT employed a three-bladed rotor and had the facility to vary rotation speed via a DC generator and change the rotor yaw and blade pitch angle. The size of the rotor was constrained by the dimensions of the water channel in which the testing would be performed. A rotor diameter of 0.4 m was chosen so that it would occupy approximately half the depth of the channel representing a similar ratio to that expected of full scale MCTs (European Commission, 1996). The blockage ratio (percentage of flow cross section occupied by the rotor) of the model MCT in the CWC was approximately 12%.

Wake velocity measurements were made using a standard two-hole Pitot tube and water surface elevation

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Fig. 1. Model MCT operating at yaw with tip cavitation present.

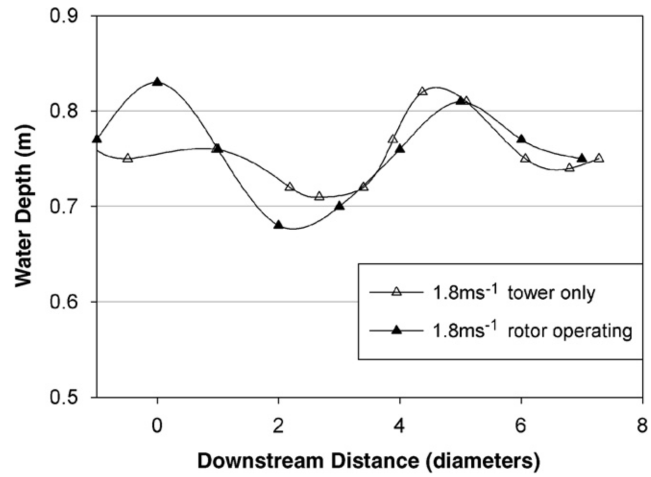

Fig. 2. Water surface elevation for 1.8 ms^{-1} wake condition.

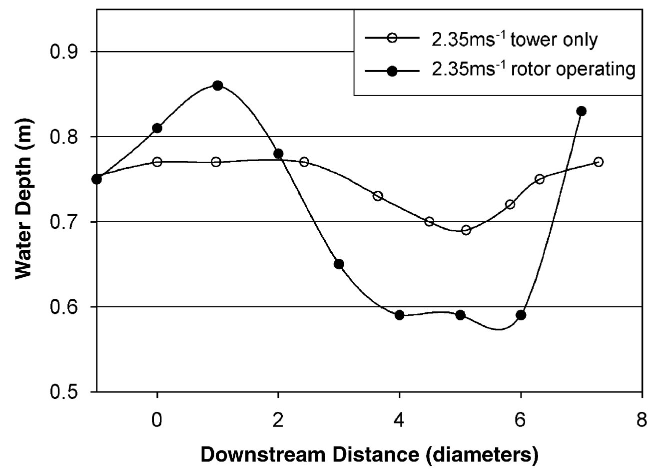

Fig. 3. Water surface elevation for 2.35 ms^{-1} wake condition.

was measured using a drop depth gauge. For the testing detailed here studies were made at three discrete flow speeds of 1.55, 1.8 and 2.35 ms^{-1} with values of rotor thrust coefficient of 0.86, 0.78 and 0.88, respectively.

Turbulence measurement was not available during the CWC tests. However, with the smooth channel sides and the presence of a honeycomb straightening mesh at the beginning of the CWC open section the flow was visually smooth. It is expected that bed roughness and other factors present in the open seas would give field measurements of turbulence greater than those present in the CWC for the model MCT tests.

3. Results and discussion

Fig. 2 shows the water surface elevation for a flow speed of 1.8 ms^{-1} with the rotor both inoperative and extracting energy from the flow. Although exaggerated by the axes the flow was only gently undulating when the rotor was inoperative, the water depth being 0.78 m at zero flow. The bulge 5 diameters downstream caused by the tower structure persisted once the rotor was operating. A clear difference can be seen in the water surface elevation once the rotor is extracting energy from the flow. The water backed up immediately upstream of the rotor and decreased downstream for 2 diameters. A pronounced increase in water surface elevation occurred between 3 and 4 diameters downstream.

Fig. 3 shows the water surface profiles for a flow speed of 2.35 ms^{-1}. A sharp decrease in water height occurred immediately downstream of the rotor when in operation and a strong standing wave (hydraulic jump) was present between 6 and 7 diameters downstream. The height of the wave was approximately 0.2 m and extended across the width of the CWC.

Two parameters were used to help explain the flow effects observed in the CWC. The first was the specific energy of a flow that is a function of the water depth and velocity. The bed slope in the CWC was zero so the gradient term was not required. Similarly, friction losses were ignored due to the smooth sides of the CWC and the short length. The specific energy is defined as

$$E = D + \frac{\alpha Q^2}{2gA^2}, \tag{1}$$

where D is the water depth, α is the energy coefficient, Q is the mass flow rate, g is the acceleration due to gravity and

A is the cross-sectional area of the flow. E is expressed in metres as is the depth and flow rate terms of (1).

The energy coefficient can be defined as

$$\alpha = \frac{\sum u^3 \Delta A}{U^3 A}, \tag{2}$$

where U is the mean velocity, A is the total flow area and u is the velocity within an elemental area ΔA. For a $1/N_{\mathrm{th}}$ power law velocity distribution the energy coefficient can be approximated as

$$\alpha = \frac{(N+1)^3}{N^2(N+3)}. \tag{3}$$

The flow profile in the CWC was uniform with depth due to a step in the bed at the inflow to the working section. Thus α was taken as unity (Chanson, 1999). Full-scale conditions will see a pronounced velocity profile and α will be greater than 1.

Flow in open channels can be classified into two types. The first is subcritical flow that is relatively tranquil, deep and with a low velocity. The second type is supercritical which is a shallow fast moving flow. Both can be defined using the Froude number which for rectangular channels can be defined as

$$F = \frac{U}{\sqrt{gD}}. \tag{4}$$

The Froude number is analogous to the Mach number used in air. For subcritical flow $F < 1$ and for supercritical flow $F > 1$. A condition known as critical depth (defined later) corresponds to $F = 1$.

Fig. 4 shows the water surface elevation, Froude number and specific energy conditions for a flow speed of $1.8\,\mathrm{ms}^{-1}$. At all points along the channel the flow was classed as subcritical. The specific energy did drop across the rotor but recovered at the far end of the channel close to the outlet. This was due to the undulating nature of the flow and the difficulty in ascertaining the average velocity at several downstream cross sections. In addition to this the power extracted by the rotor was relatively small in comparison to the overall available energy in the channel. Approximately 6% of the kinetic energy in the channel was extracted by the MCT rotor.

The water surface profile was most interesting for the greatest flow speed tested at $2.35\,\mathrm{ms}^{-1}$. Fig. 5 shows that as with the previous cases the water surface elevation decreases immediately downstream of the rotor. For the $2.35\,\mathrm{ms}^{-1}$ wake study the flow passed through critical depth ($F = 1$) and then became supercritical. A strong hydraulic jump formed between 6 and 7 diameters downstream of the rotor. The cause of the hydraulic jump was probably due to the dimensions of the outlet to the CWC backing up the flow. A weak jump was formed ($1 < Fr < 2$) which meant that only a small amount of energy was dissipated by the turbulent flow within its structure. A detailed profile of the cross-section velocity could not be taken (due to time constraints) meaning the energy loss across the jump could not be accurately ascertained.

Critical depth is of interest to the subject of open channel flow. It is a condition in between subcritical and supercritical flow and occurs when the Froude number is equal to unity. Critical depth is that which requires the least amount of energy to convey a flow of water. However, in design of artificial channels it is avoided as small changes in specific energy result in large variations in depth leading to an unstable flow (Chow, 1959). The equation that defines critical depth for a rectangular channel is

$$D_{\mathrm{c}} = \left(\frac{Q^2}{gB^2}\right)^{1/3}, \tag{5}$$

where B is the breadth or width of the channel. So for each case in the CWC the critical depth is dependant upon the flow rate. The velocity profile at the inlet was uniform with depth this can be ascertained with a good deal of accuracy. Fig. 6 illustrates the relationship between specific energy and depth for a constant flow rate. D_{c} and E_{c} are the critical depth and energy, respectively. It can be seen that when energy is extracted from a subcritical flow ($Fr < 1$) the

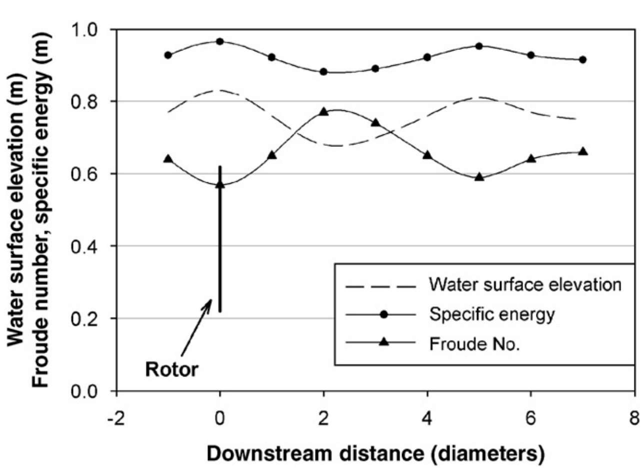

Fig. 4. Flow characteristics with rotor operating at $1.8\,\mathrm{ms}^{-1}$ inflow velocity.

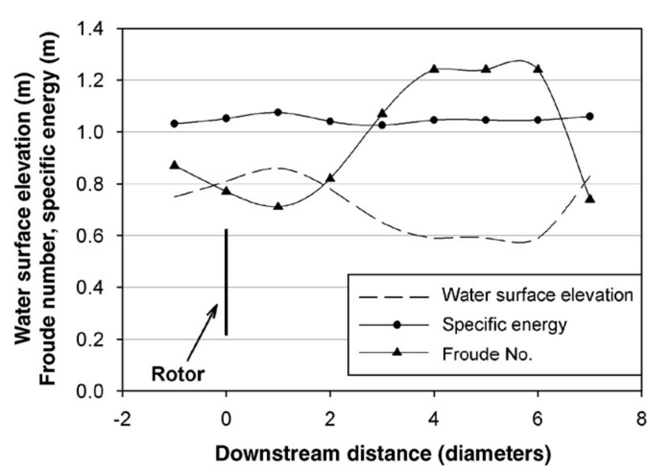

Fig. 5. Flow characteristics with rotor operating at $2.35\,\mathrm{ms}^{-1}$ inflow velocity.

depth decreases. The opposite is true when energy is removed from a supercritical flow. For any value of specific energy (E_x) there are two possible depths of flow; one subcritical (D_2) and one that is supercritical (D_1).

The value of critical depth and the water surface elevation for all three wake studies can be predicted by plotting a graph of specific energy versus depth. This can then be used to validate the measured values. Fig. 7 shows the theoretical specific energy/depth curves for all three wake cases and the measured values of specific energy for the $2.35\,ms^{-1}$ case. This corresponds exactly to the theoretical curve. For the $2.35\,ms^{-1}$ wake study the critical depth was given as 0.68 m which occurred at 2 diameters downstream of the rotor (see Fig. 5) and also for a point half-way along the standing wave at approximately 6 diameters downstream. Fig. 7 gives a good estimate of the water surface elevation before and after the hydraulic jump. For a specific energy of a little greater than 1 m the two corresponding depths at the hydraulic jump are 0.6 and 0.8 m which correspond to experimental measurements shown in Fig. 5.

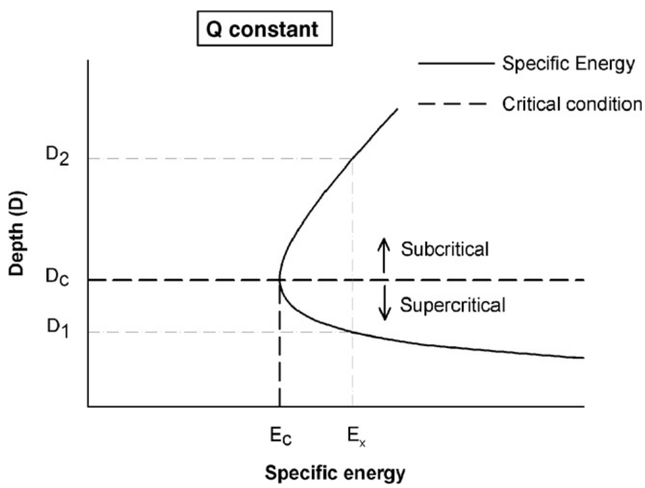

Fig. 6. Specific energy/depth curve for constant flow rate.

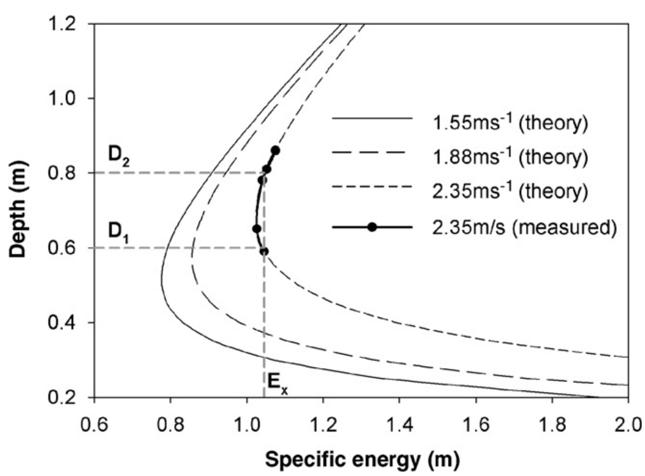

Fig. 7. Theoretical and measured variation of specific energy with water depth.

Finally, the increase in water surface elevation between 3 and 4 diameters downstream for the $1.8\,ms^{-1}$ wake study was found to be effected by the wake expanding to reach the surface. From measurements of the lateral expansion of the wake it was assumed that it would also expand vertically at the same rate. Fig. 8 shows the wake expansion imposed upon the water surface profile. The increase in elevation 4 diameters downstream coincides well with the predicted expansion. This correlation was also demonstrated for an inflow speed of $1.55\,ms^{-1}$ (not shown) with good agreement. At an inflow speed of $2.35\,ms^{-1}$ the expanding wake could not be shown to reach the surface in such a manner due to the more extreme flow effects.

4. Conclusions

The water surface elevation profiles for the model MCT in the CWC can be explained as such:

1. An increase depth upstream of the rotor due to the physical blockage and a slowing of the water across the rotor disk.
2. A decrease in depth immediately downstream due to the rotor extracting energy from a subcritical flow (see Fig. 6) and a blockage effect.
3. An increase in depth further downstream for the $1.8\,ms^{-1}$ case (and $1.55\,ms^{-1}$ not shown) due to the wake reaching the surface. For the $2.35\,ms^{-1}$ case this was due to the triggering of a hydraulic jump causing the supercritical flow to return to subcritical. This was probably caused by the dimensions of the working section outlet.

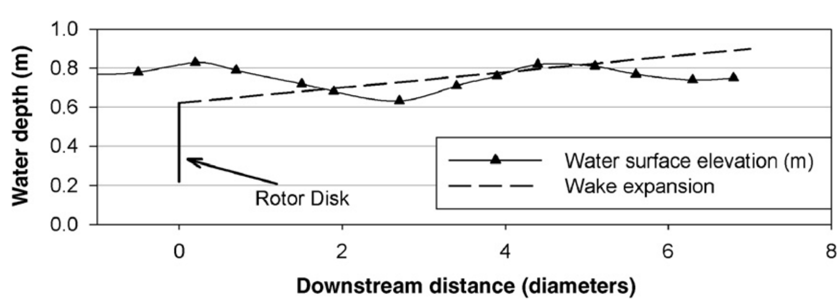

Fig. 8. Wake expansion at $1.8\,ms^{-1}$ as expected from determining α from lateral wake measurements.

Full-scale devices are unlikely to experience such extreme changes in water surface elevation. Froude numbers for deeper flows (<0.2) are much lower than those occurring at model scale. Thus changes in depth caused by the removal of energy will be smaller. However, in areas where there may be raised sections of seabed cumulative depth reductions downstream of a number of MCTs may cause the depth to approach D_c which may cause severe undulations in the water surface profile. Rotor clearance will be increased when in operation compared to that at zero flow due to the slowing of fluid across the rotor disk and a subsequent increase in depth. Experimental work in the CWC has shown that the location of this 'bulge' above the rotor moves downstream with increasing flow speed perhaps due to increased shear. This effect may allow slightly larger diameter rotors to be installed than previously thought as once operating the clearance to the surface will increase. As all full-scale devices will be operating in subcritical flow there will be a reduction on depth downstream of the rotor when energy is being extracted from the flow. Finally, expanding wake flow may reach the surface and increase the depth further downstream of the rotor or mix with wake flow from an adjacent MCT. The rate of expansion will depend upon the ambient turbulence intensity and the thrust coefficient of the rotor.

It is uncertain at this time how much of the unusual flow profiles were due to the blockage-type effects of the rotor or the extraction of energy. For a location where the bed slope is small or zero the energy conveyed by the flow will be a function of depth and velocity. The presence of operating MCTs will alter both of these terms by presenting a semi-permeable object and removing energy. Accurate quantification of the water surface profile around an array of devices will prove a challenge. Wake velocity measurements made in the CWC indicated that flow was accelerating around the sides of the rotor at all flow speeds and this effect became more pronounced at greater inflow speeds. This may suggest a Froude number scaling effect. It is expected that increasing the area of a channel occupied by rotors will cause more extreme blockage-type effects such as flow acceleration around the sides of the rotors and more extreme water surface profiles. Thus there may be a practical limit to the cross-sectional area of MCTs within any given channel.

The effects of varying blockage ratios, wake expansion and Froude number scaling within multiple rows arrays of MCT-type devices requires investigation before the first arrays are installed.

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