Impact of scaled tidal stream turbine over mobile sediment beds

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***Abstract*—Tidal stream turbines (TST) have been identified as a desirable technology for harnessing tidal energy. Measurement and characterisation of wakes are critical for environmental and development reasons. Wake recovery length is an important parameter for appropriate design of arrays, and wakes may result in altered dynamics both within the water column and at the seabed. Laboratory-scale experiments over mobile beds have been conducted to quantify the detailed wake structure and its impact on sediment transport dynamics. A 0.2 m diameter model turbine was installed and a steady current was driven over an artificial sediment bed using recirculating pumps. A Nortek acoustic current-meter Aquadopp was used to measure the three-dimensional mean current with vertical profiles at different locations from the turbine. A three-dimensional Acoustic Ripple Profiler was used to map the bed during the experiments. These measurements provide comprehensive data sets which can be combined to (i) characterise wakes, bed disturbances, and the impact on suspension processes and, (ii) used to inform and validate numerical models.**

***Keywords*—Tidal stream turbines, laboratory experiments, environmental impact, mobile sediment bed, wakes.**

I. INTRODUCTION

The need of sustainable energy has led in recent years to the development of tidal stream turbines (TST) and has become a near reality. A number of renewable energy sources are available around the world from water, geothermal heat, sun, wind, biomass and wave-tidal sources. However, different issues have made their use extremely difficult: conversion processes, limited efficiencies, infrastructure, land availability, systems reliability and the impact to the environment are all important factors in energy extraction [1]. TST take advantage of the well known and predictable tidal current behaviour, which also represent a predictable energy generation. In addition, TST are thought to be a better option than tidal barrages because of a smaller impact impact on the environment. Examples of this new technology are the prototype devices that have been tested by different companies throughout government support such as *Marine Current Turbines*, *Lunar Energy*, *SMD Hydrovision*, *Pulse* and *TGL* [2].

While a comprehensive list of impacts of TST on their environment has yet to be determined, effects on the flow field and the sea bed are important. An accurate characterisation of the changes in the flow field and thus the wake will help to determine the distance between turbines in order to achieve the maximum efficiency. The presence of the device will result in a decrease in current velocity but will recover after a certain distance downstream. Determining the optimal distance between turbines therefore has to balance the decrease in efficiency of energy extraction due to proximity with the increase in installation cost due to overall size of TST farm. The effect of a turbine on the sea bed is less known. Nevertheless, turbulence produced by TST can have an impact if they are too close to the sea bed with possible changes in the normal sediment transport pattern. Experiments with disks have shown important changes in: i) turbulence structure depending on the proximity to the sea bed, ii) increase in turbulent intensity over a roughened bed and, iii) far downstream, effects of the wake with a combination of distance to the sea bed and roughness [3].

Impacts of TST on sediment transport may take different forms. A first scenario could be to avoid the effects by placing the turbines far enough from the sea bed. This will require the knowledge of the total water depth at which no impacts are expected and would limit the number of possible sites as deeper waters will be necessary. On the other hand, the TST will increase the erosion near the rotor, take sediment in suspension and transport it downstream. This sediment could be added to the sediment eroded by the next turbine and finally deposited some distance downstream from the entire TST farm. However, the sediment could be transported again with the reversing of the flow. These mechanisms are not well known and depend on the modifications of the flow field by the presence of a turbine. The present study focuses on the

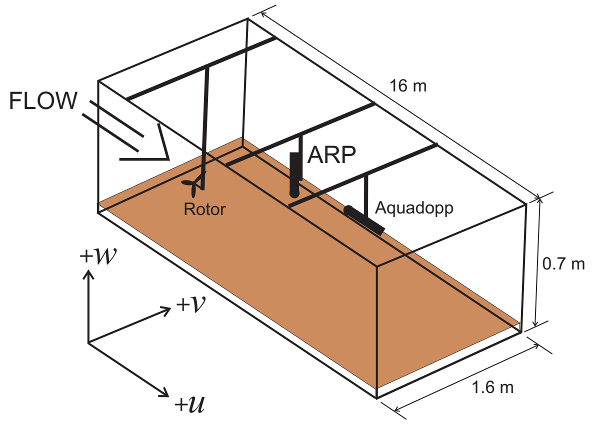

Fig. 1. Scheme of the configuration of the experiments with the model turbine and measuring instruments in the TES flume and the coordinate system showing positive directions of the velocity components used in this study.

characterisation of the changes in the flow field and sea bed in the presence of a turbine. The experiments in this investigation were carried out using a scaled turbine rotor and a mobile artificial sediment bed to better simulate real field conditions.

II. METHODS

A series of experiments were carried out in the Total Environment Simulator (TES) flume of the University of Hull, United Kingdom. The flume is 16 m long and 1.6 m wide. The flume is equipped with pumps to re-circulate water creating a steady current of about 0.5 m·s^{-1}. A sediment bed 0.1m thick was created and consisted of sand of about 425 μm with density of 2650 kg·m^3. The flume was then filled with freshwater to a water height of 0.5m over the rigid surface of the flume floor. The horizontal axis model turbine had a 0.2m diameter and was mounted in a gantry over the flume (Fig. 1). The diameter of the turbine was used as a reference distance, D=0.2m, during all the experiments.

Two experimental conditions were measured. The first series of measurements consisted of characterisation of the flow without the turbine installed in the flume and the second series with the turbine to observe the changes occurring in the flow field and the sediment bed. The velocity field reported here was measured using an Aquadopp from *Nortek AS*. The instrument was mounted on a mobile gantry which allowed measurements to be taken at different positions in a predetermined grid as shown in figure 2. It recorded at 2 Hz during 10 minute periods in cells of 0.02 m.

It is common to find spikes in acoustic measurements due to aliasing of the Doppler signal. A filtering technique by [4] was used to clean the data in the horizontal direction, i.e., each 10 minute time series burst and vertical cell level was treated separately. The 10 minute cleaned bursts were then averaged to obtain one profile for each measured position.

The evolution of the sediment bed was measured using a *Marine Electronics* three dimensional sand ripple profiler or ARP [5]. The ARP measures the amplitude echo due to the sea bed in a cross-section at an angle of about 150 degrees. It rotates measuring sections of the sea bed until a complete circular bed area is scanned. For the experiments in this study, the ARP was mounted at a fixed position in the horizontal plane of 0.43m from the turbine measuring sections of the bottom at 0.9 degrees. Figure 3 shows an example of observations taken with the ARP profiler. A rotation was carried out in order to align the data with the main current in the flume. A square central section of 1.4m^2 was extracted for the analysis presented in this study, which is 0.2m smaller than the flume width in order to avoid the effects of the walls on the echo signal.

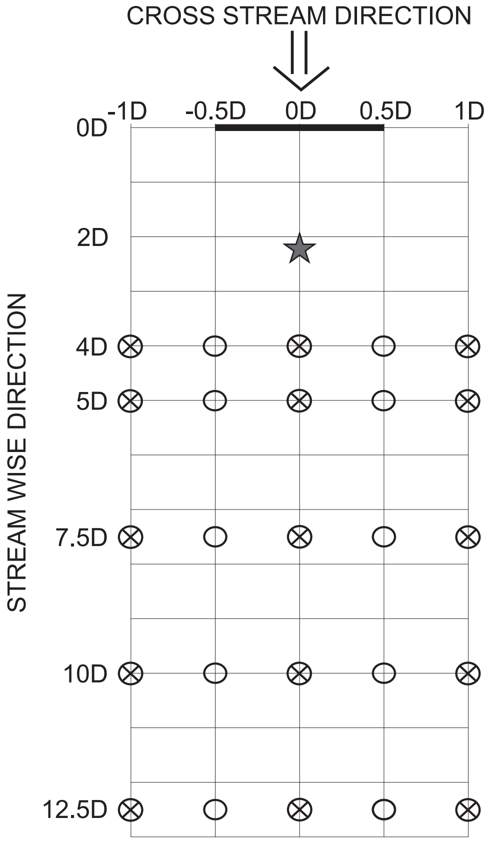

Fig. 2. Measurement positions in rotor diameters (D=0.2m). Circles are measurement positions with rotor installed in the flume. Circles with a cross inside are positions where also measurements without rotor were taken. The $0D$,$0D$ is the rotor position and the arrow marks the direction of the flow.

III. RESULTS

A. *Velocity profiles*

Figures 4-6 show the velocity profiles for u, v and w velocity components respectively. The u velocity component (Fig. 4) along the channel without the turbine installed (blue lines) was characterised by high magnitudes of more than 0.5 m·s^{-1} at the surface with a shear which decreased the velocity magnitude to values about 0.3 m·s^{-1} at the bottom. The minimum u value, close to 0 m·s^{-1}, was recorded at $4D$,-$1D$ position while the maximum at $7.5D$,$1D$ position. Overall, a similar boundary layer is present in all the profiles without the turbine with important velocities near the bottom.

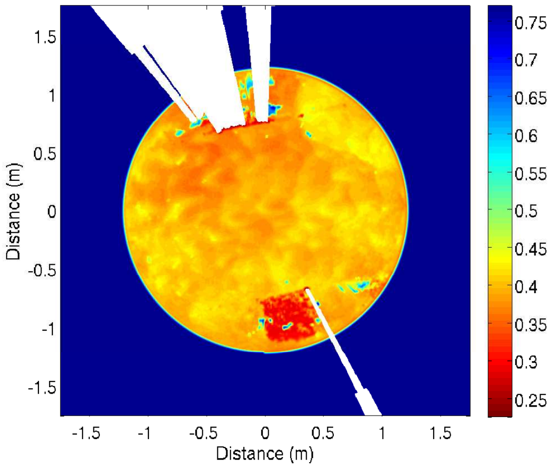

Fig. 3. Example of a sequence of measurements obtained with the acoustic ripple profiler (ARP). The instrument is orientated down-looking and takes a swath of 150 degrees of a cross section of the sediment bed in parts of 0.9 degrees. Then rotates 0.9 degrees to measure another swath and continues until a complete circle is reached after 200 swaths corresponding to 180 degrees. White sections correspond to effects of the flume walls and the color scale is the distance from the transducer height to the bed.

Important changes in velocity profiles with the turbine present in the flume were found (red lines). A decrease in magnitude is the first obvious feature in all the profiles except at 4D,-1D position, where both profiles with and without turbine have similar structure and magnitude. The difference in magnitude reaches approximately 0.4 m·s^{-1} for the velocity profile with the maximum velocity without the turbine (7.5D,1D). The vertical structure of the profiles with turbine is similar in the upper two thirds of the water column but the presence of the model turbine results in an increase of the near-bed shear. Velocities near the bottom decreased to near zero or negative values.

There are important cross-channel differences four diameters downstream of the turbine. While little impact of the turbine can be observed at -1D, the wake is most pronounced at 0D directly behind the turbine. At 5D and 7.5D distances, the turbine wake seems to have the strongest effect on the velocity profiles while at 10D and 12.5D, a slight recovery is noticeable at -1D positions.

Velocity profiles for the v component (Fig. 5) show smaller magnitudes and structure as expected. Magnitudes without the rotor installed were less than 0.1 m·s^{-1} with the only exception at position 4D,-1D where a positive velocity reached 0.1 m·s^{-1} during most of the profile. Slight changes in direction of the flow are present in some of the profiles but the magnitudes are still low. Spikes are also present near the bottom in some profiles maybe due to effects of the boundary on the acoustic signal. Profiles with the turbine installed showed a velocity decrease to near zero values at 4D stream wise with -1D and 0D distances while an important increase occurred at 1D distance, where the velocity reached more than 0.1 m·s^{-1} meaning that fluid movement to the left of the main flow is significant. No important changes of v velocity profiles were found along the channel at positions 5D to 10D stream wise and -1D cross stream directions. At these same stream wise directions and 0D and 1D cross stream there were changes in the direction of the v velocity but always maintained low magnitudes. At 12.5D,0D distance, the magnitude increase to near 0.1 m·s^{-1} with a negative direction while at 12.5D,-1D a positive direction is present although about 0.05 m·s^{-1}. These two profiles had an important shear near the bottom.

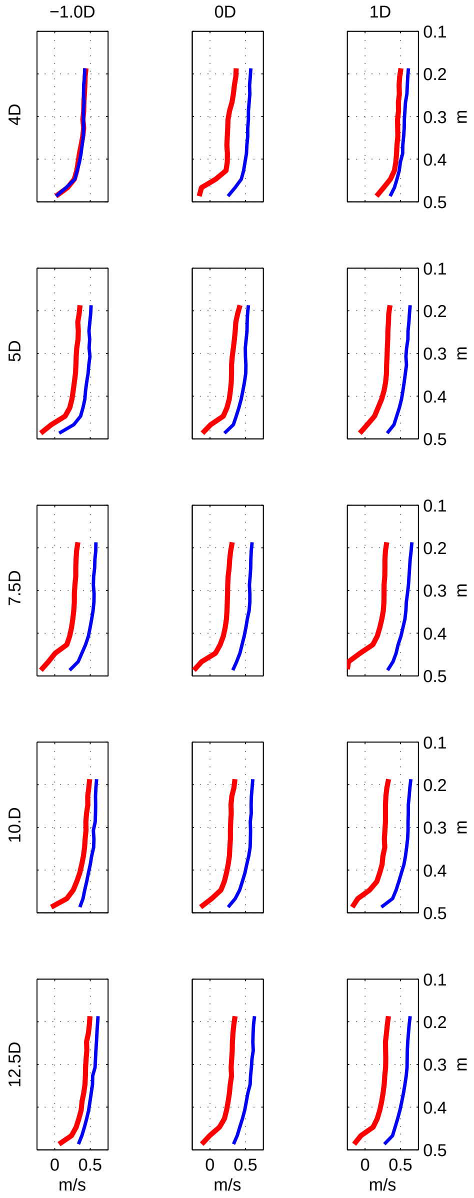

Fig. 4. Profiles of u velocity component. Upper and left numbers indicate the horizontal position of each profile relative to turbine diameters D. Blue lines are profiles measured without the scaled turbine installed while red lines with the turbine in the flume at 0.15m from the bottom. The turbine was installed horizontally at 0D,0D stream and cross wise directions respectively. Thus, profiles start at about 0.8m from the turbine.

The vertical component w is shown in figure 6 with the most

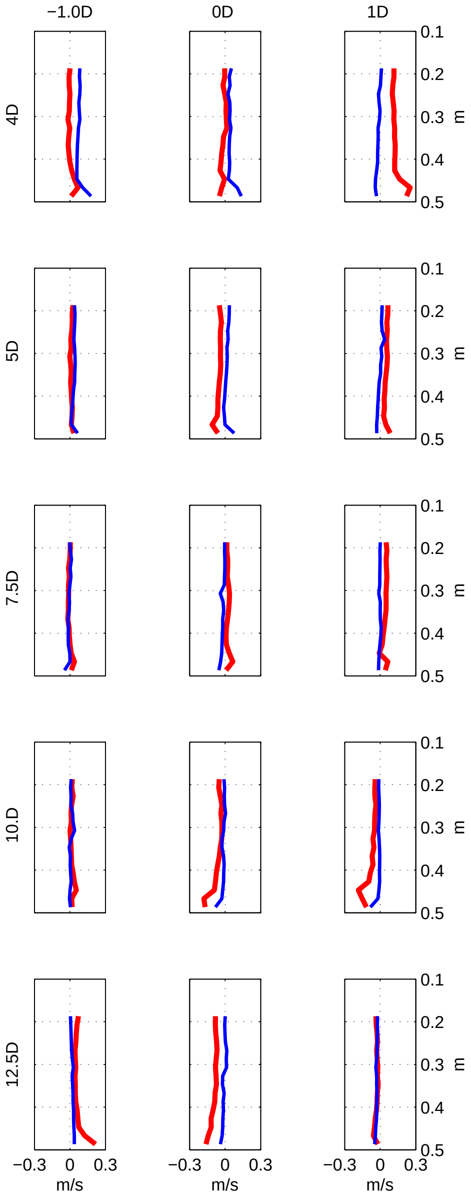

Fig. 5. Profiles of v velocity component presented as in fig 4 but with change in velocity scale to notice the vertical structure.

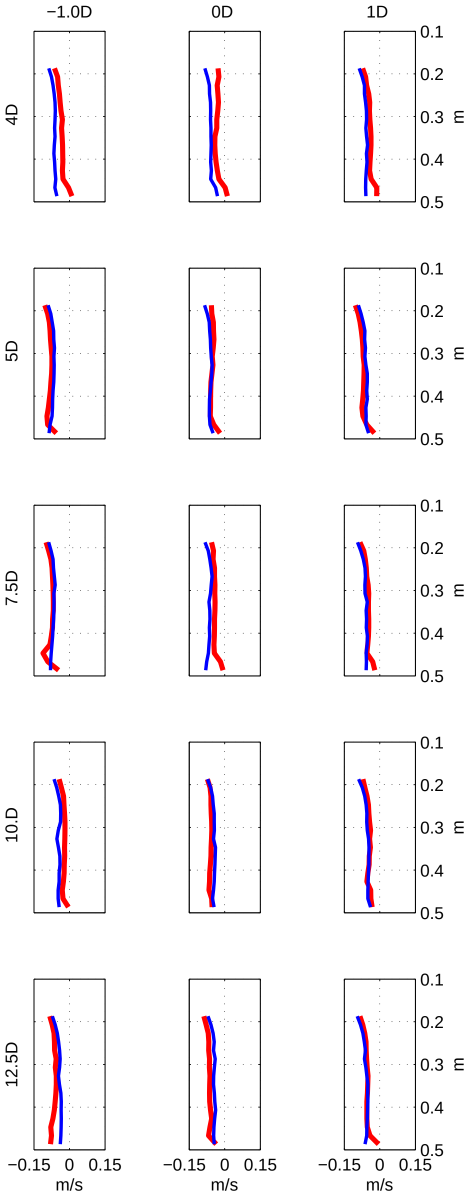

Fig. 6. Profiles of w velocity component presented as in fig 4 but with different velocity scale than those used in figures 4 and 5.

important characteristic being that all velocities are negative in both with and without the turbine in the flume. Magnitudes reach about -0.1 $\text{m}\cdot\text{s}^{-1}$ at surface and diminishing throughout the water column to approximately -0.05 $\text{m}\cdot\text{s}^{-1}$ near the bottom. Only velocity magnitudes at $4D$ distance presented a slight decrease in magnitude when the turbine was installed in the flume.

B. *Bed evolution*

Figure 7 shows the changes in the bed throughout the experiment. Figure 7a shows the bed morphology before the measurements with the Aquadopp were taken while figure 7b shows the sediment bed after the experiments. Important changes can be seen in the measured area. In particular, a horse shoe shape scour is present just behind the turbine with deposition of sediment in the middle. Deposition also occurred at the right, near the flume wall, which is also present without the turbine but this seems to enhance the deposition rate.

The change in volume can be estimated using the difference between heights after and before the experiments and assuming that each point measured by the ARP is representative of an area of approximately $2.3\times10^{-5}\text{m}^2$. The sediment mass is in turn calculated assuming sediment density of 2650 $\text{kg}\cdot\text{m}^3$. The gain or loss of mass is shown in figure 7c where positive values represent deposition and negative values represent erosion. From the total area, 75% presented deposition of about 68.5 kg while only 7.7 kg were eroded in the remaining

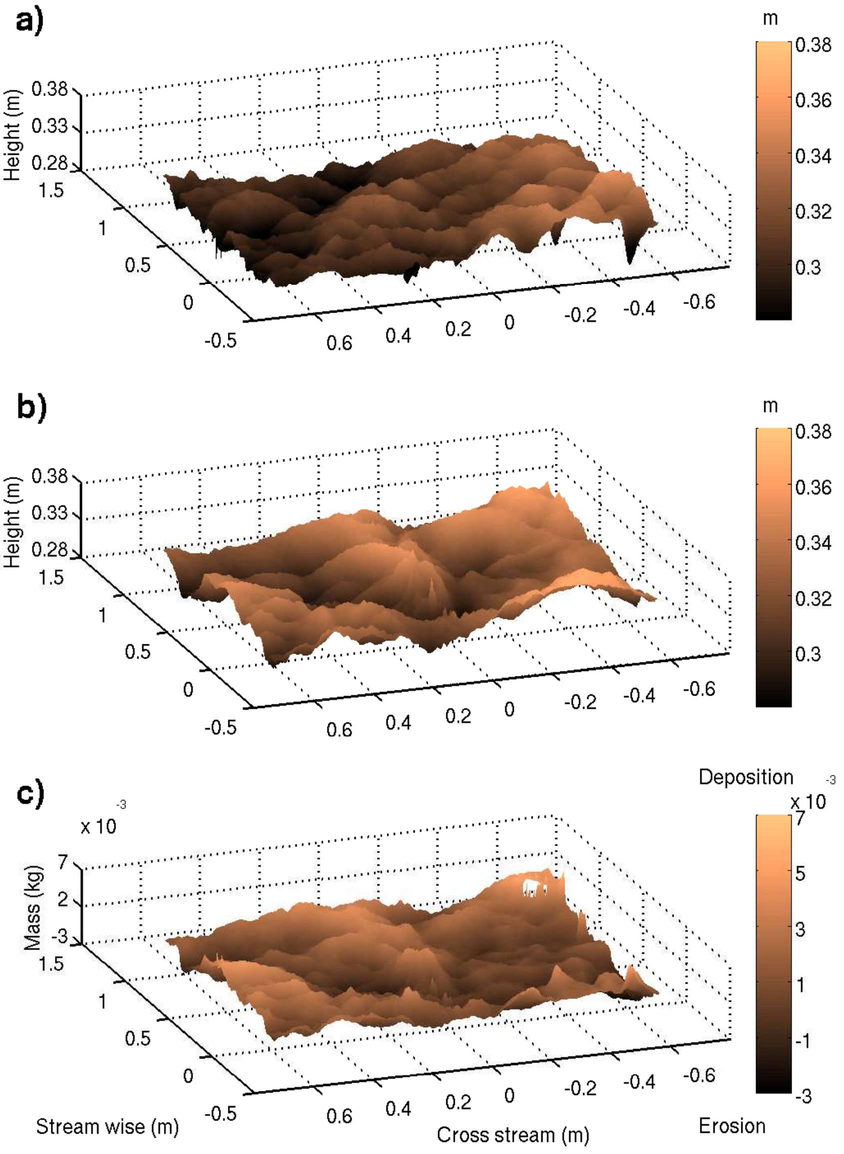

Fig. 7. Bed morphology based on measurements with the three dimensional sand ripple profiler (ARP). The turbine was located at 0,0 horizontal position. Vertical axes in (a) and (b) are the height of the sediment over the flume floor. a) before the experiments, b) at the end of the experiments and c) is sediment mass due to deposition or erosion as positive and negative values respectively.

25% which represent a net deposition of 60.8 kg. The time difference between the bed morphology of (a) and (b) in figure 7 was about 48 hours. Therefore, a deposition rate of about 1.2 kg·hr^{-1} was present in the flume during the experiments.

IV. Discussion and Conclusions

A reduction in velocity was obtained in the experiments with the turbine installed as is commonly found in this type of experiments. The effects of the turbine on the velocity were present along the measured distance in the flume with only signs of flow recovery at one of the sides, right part of the flow while other locations maintained a strong difference with the conditions without the turbine. This result contrasts with studies that show a rapid flow recovery after $7D$ to $12D$ distance from rotors or disks (e.g. [3], [6], [7]). These findings highlight the importance of the mobile bed in the flow and the need of further studies including the modifications to the flow. Using numerical modelling, reductions in current velocity of about 0.3 m·s^{-1} have been found as a possible result of the installation of a TST farm in an estuary [8].

The evolution of the sea bed showed interesting sediment dynamics resulting in scour near the turbine but also deposition in the far region. The scour is consistent with studies that show decrease in velocity in the near wake on both sides of the turbine and an increase far from the turbine in the cross wise direction [7]. This could explain the deposition of sediment in the middle section and the scour at the sides in a horse shoe shape. Numerical modelling have also shown that TST farms could have effects on deposition/erosion at a distance of 50 km [9].

According to the results of the present investigation, the combination of both the turbine and mobile bed lead to important changes in both hydrodynamics and geomorphology. Important decrease in velocity speed in the entire water column was found and almost no flow recovery was recorded after 12.5D downstream distance from the turbine. An erosion area with a horse shoe shape was generated near the turbine and deposition at the central part and the far right side of the flume which seems to be the result of the enhancing erosion/deposition patterns before the presence of the turbine.

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