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Tidal power extraction on a streamwise bed slope

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Three-dimensional Reynolds-averaged Navier–Stokes computations are presented for an actuator disc representation of an ideal tidal stream energy extracting device, operating within a channel that slopes in the streamwise direction. Downwards facing, horizontal and upwards facing slopes are considered at the same mass flow rate and depth at the device position, for both high and low channel blockage ratios. The downwards facing slope is shown to present a greater available kinetic power to the disc than the horizontal and upwards facing slopes. This is due to the velocity profile being more strongly sheared as a result of the adverse pressure gradient, which results in greater thrust variation over the disc area. Conversely, during uphill flows devices experience reduced thrust variation, as the velocity profile is more uniform due to the favourable pressure gradient. Although downhill flows can deliver greater overall power due to increased flow shear, uphill flows are more efficient at converting the power presented to the disc into power removed and this is shown to be due to the downstream flow constriction and resulting increased pressure coefficient drop through the bypass flow.

1. Introduction

Large bathymetric features of the order of the rotor diameter D (such as bed ridges, troughs and hills) induce local changes in the velocity boundary layer, which may lead to considerable unsteady loading on tidal devices if they are not sited optimally. An improved understanding of the influence of such large bathymetric features may be used to better advise the placement of future tidal devices, which are currently positioned, based on the local depth, bed condition and predicted mean velocity profile alone. To this end, several authors have used computational fluid dynamics (CFD) with high fidelity bathymetry data and acoustic doppler current profilers (ADCP), to predict the local flow field at prospective tidal sites. Zangiabadi et al. (2015) used large eddy simulation (LES) and steady state Reynolds-averaged Navier–Stokes (RANS) computations to study the local flow field of a potential tidal stream installation site in Ramsey Sound, Wales. They observed the wake structure and vortices shed from Horse Rock (a submerged pinnacle) and obtained good agreement with ADCP transects of the local flow field. Evans et al. (2015) studied the same site in Ramsey Sound and suggested that the wake recovery behind the submerged pinnacle was influenced both by the velocity magnitude in the flow direction and the local bathymetry. Soto and Escauriaza (2015) computed the local flow field through the Chacao channel in Chile, using LES and an actuator disc representation for an array of tidal energy devices. They found that even small bed features led to significant changes in the velocity boundary layer upstream of the discs, adversely affecting the performance of the entire array. When validating a high fidelity CFD simulation of the Minas Passage in Canada, Wilcox et al. (2015) identified a volcanic planform (bed ridge) that lead to a large separation bubble, similarly to flow over a backwards facing step. The high levels of turbulence generated from the volcanic planform and from a nearby island were subsequently highlighted as areas to be avoided for device installation, in order to mitigate unnecessary fatigue damage.

The high computational cost associated with sufficiently resolving real bathymetric features both spatially and temporally has led some authors to analyse simplified bathymetric features instead. Draper et al. (2013) and Edmunds et al. (2014) both independently considered an idealised tidal headland site and the effect of tidal energy extraction on the local undisturbed flow field. The results of these studies highlighted that given the local bathymetry of a potential tidal stream energy installation site, improved device performance could potentially be achieved with careful choice of device location, operating point and local blockage. In addition, changes to the local flow field due to the presence of the devices may adversely affect the rates of sediment transport, volume flow rate through the channel and lead to other environmental consequences, if not properly considered.

In this study, the interaction of a simplified general bathymetric

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Nomenclature

B	blockage ratio (–)
ΔB	log-law intercept modification (–)
c_f	skin friction coefficient (–)
C_p	power coefficient (–)
C_p'	alternative power coefficient (–)
C_{pre}	static pressure coefficient (–)
ΔC_{pre}	static pressure coefficient drop across the disc (–)
C_s	roughness constant (–)
C_T	thrust coefficient (–)
C_T'	alternative thrust coefficient (–)
D	device or disc diameter (m)
E	empirical constant (–)
$\Delta \dot{E}$	change in total energy flux (W)
g	acceleration due to gravity ($\mathrm{m^2/s^2}$)
G	cell growth ratio normal to the wall (–)
h	local fluid depth (m)
Δh	change in local free surface height (m)
H	diffuser inlet height or fluid depth at the disc plane (m)
k	turbulent kinetic energy ($\mathrm{m^2/s^2}$)
K	momentum loss factor (–)
K_s	roughness height (m)
K_s^+	dimensionless roughness height (–)
$\dot{m}$	mass flow rate (kg/s)
$\hat{\boldsymbol{n}}$	unit normal vector (–)
p	static pressure ($\mathrm{N/m^2}$)
p_{ref}	reference static pressure ($\mathrm{N/m^2}$)
Δp	static pressure drop across the disc ($\mathrm{N/m^2}$)
R	diffuser corner radius (m)
Δr	radial cell length at the disc edge (m)
s	device tip to tip spacing (m)
δT	local thrust increment (N)
$\boldsymbol{U}$	Reynolds-averaged velocity vector (m/s)
U_b	bulk velocity (m/s)
U_d	velocity normal to the disc plane (m/s)
U_{d0}	velocity normal to the disc plane with no device (m/s)
u_τ	friction velocity (m/s)
$\overline{u^2}, \overline{w^2}, \overline{uw}$	Reynolds-stress components in the $x-z$ plane ($\mathrm{m^2/s^2}$)
U, V, W	Reynolds-averaged velocity components (m/s)
x, y, z	Cartesian coordinates (m)
Δx	streamwise cell length at the disc plane (m)
y^+	non-dimensional wall normal distance (–)
z_0	wall adjacent cell centroid height (m)
ϵ	dissipation rate ($\mathrm{m^2/s^3}$)
κ	empirical constant (–)
ν	kinematic viscosity ($\mathrm{m^2/s}$)
ν_t	kinematic eddy viscosity ($\mathrm{m^2/s}$)
ρ	fluid density ($\mathrm{kg/m^3}$)
θ	slope angle (°)
τ_w	wall shear stress ($\mathrm{N/m^2}$)
ω	specific dissipation rate ($\mathrm{s^{-1}}$)

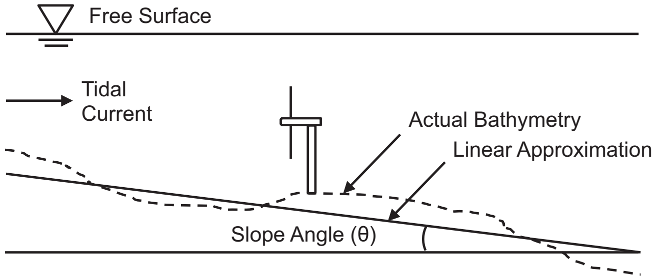

Fig. 1. An approximation of large bathymetric change, of the order of the device diameter (such as a bed ridge) by a constant slope angle θ.

feature with an ideal energy extracting device (representing an axial flow tidal turbine) will be considered. The observations made in this work may be useful when selecting potential tidal stream energy sites and identifying key flow features, before high fidelity CFD studies or ADCP measurements are performed. As shown in Fig. 1, a first approximation to local bathymetric changes can be made by a constant (positive or negative) slope in the streamwise direction. Slope variations in the cross stream (lateral) direction (as may occur near a coastal headland, Draper et al., 2013) can be approximated in a similar manner and may be considered in future work. This study presents results for streamwise bed slopes only.

In this investigation a series of computational studies were performed, to investigate the steady flow changes induced by such a general bed feature. Unsteady flow features such as vortex shedding (induced by bed hills, pinnacles and sharp headlands) were not considered. It should be noted that inviscid, analytical models (such as those of Garrett and Cummins, 2007; Houlsby et al., 2008; Whelan et al., 2009) cannot be applied directly to the current problem. This is primarily because the surface pressure distribution acting on the inclined bed surface cannot be readily determined and hence the momentum balance remains unclosed. However, the analytical solution for a similar tidal channel with zero bed slope (using the model of Garrett and Cummins, 2007; Houlsby et al., 2008; Whelan et al., 2009) can still be used to provide a useful reference point and will be presented alongside the computational results in this investigation.

Before presenting the results for idealised tidal turbines, a validation study was performed. This was to ensure that the turbulence and wall modelling approaches were sufficient to predict the wall shear stress variation (and hence the developing velocity boundary layer) on the inclined bed slope. In particular, accurate modelling was essential for the downwards facing slope, which was susceptible to flow separation due to the adverse pressure gradient.

2. Turbulence model validation study

Obi et al. (1993) investigated the separation and subsequent reattachment of fully developed turbulent flow from the smooth surface of a nominally two-dimensional asymmetric diffuser. This study was chosen as a test case for several reasons. Firstly, it had been adopted as a benchmark test in the IAHR/ERCOFTAC workshop to assess the performance of turbulence models (Hellsten and Rautaheimo, 1999). Secondly, the measurements were independently verified with a repeat experiment by Buice and Eaton (1997) using hot wire probes. Their measurements of the core flow variables were in excellent agreement with the data set of Obi et al. (1993). In addition, they added skin friction (τ_w) measurements (for the inclined wall) to the data set and extended the region of mean flow measurements further downstream. Skin friction measurements were essential to determine the separation point.