Flores Mateos, L. M.; Hartnett, M.

Article

Tidal-stream power assessment: A novel modelling approach

Energy Reports

Provided in Cooperation with:
Elsevier

Suggested Citation: Flores Mateos, L. M.; Hartnett, M. (2020) : Tidal-stream power assessment: A novel modelling approach, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 1, pp. 108-113,
https://doi.org/10.1016/j.egyr.2019.08.027

Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 6 (2020) 108–113
www.elsevier.com/locate/egyr

6th International Conference on Energy and Environment Research, ICEER 2019, 22–25 July, University of Aveiro, Portugal

Tidal-stream power assessment—A novel modelling approach

L.M. Flores Mateos*, M. Hartnett

College of Engineering and Informatics, NUI Galway, H91 TK33 Galway, Ireland
Ryan Institute, NUI Galway, H91 TK33 Galway, Ireland
Centre for Marine and Renewable Energy Ireland (MaREI), Cork, Ireland

Received 1 August 2019; accepted 20 August 2019

Abstract

An alternative approach for simulating turbine array energy capture, momentum sink-TOC, was developed to improve conventional methodologies for assessing tidal-stream energy resource. The method uses a non-constant thrust force coefficient calculated based on turbines operating-conditions and relates turbine near-field changes produced by power extraction to turbine thrust forces. Momentum sink-TOC was implemented in two depth-average complex hydrodynamic models to simulate an ideal turbine lay-out to perform tidal-stream energy resource assessment. The first model solves smooth and slow flows (SSF). The second model solves rapidly varying flows (RVF). Calculation of head drops across the turbine arrays and turbine efficiencies enabled estimation of further power metrics. Tidal-stream energy resource evaluation with a tidal fence indicates that a computationally economical pre-assessment can be adequately performed using an SSF solver. However, caution should be taken when using SSF solver due to the incapacity of the model to accurately solve velocity reduction due to power extraction.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Keywords: Actuator disc; Thrust coefficient; Open channel flows; Shock-capturing capability

1. Introduction

A more realistic analytical model to analyse coastal tidal-streams energy capture by marine turbines is the Linear Momentum Actuator Disk theory (LMADT) within open channel flows (LMAD-OCH). The analysis of energy capture considers the influence of bottom and surface boundaries in the tidal-stream and the existence of a down-stream turbine-mixing region [1], where power extraction produces a head drop (Δh) over the turbine array. LMAD-OCH has been used to analyse power extraction from bounded flows through a turbine configuration that covers completely the cross-section of a channel referred to as tidal fence [2]; and from un-bounded flows through

* Corresponding author at: College of Engineering and Informatics, NUI Galway, H91 TK33 Galway, Ireland.
E-mail address: l.floresmateos1@nuigalway.ie (L.M. Flores Mateos).

https://doi.org/10.1016/j.egyr.2019.08.027

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

partial-fences [3]. However, implementation of LMAD-OCH is based on a shock fitting scheme [2]. This technique is rather computationally expensive and treats rapid changes generated in the tidal-stream due to energy capture as discontinuities [4]. Additionally, shock fitting technique requires the specification of a head drop across the array as an internal boundary. The aim of this paper is to evaluate tidal-stream energy resources by implementing an alternative method to simulate marine turbine's power extraction. This method referred to as momentum sink-TOC is a computationally less expensive approach for simulating sharp gradients produced by power extraction than existing techniques and is not constrained by a head drop [5]. To determine the importance of using rapidly varying flow solution procedure for assessing tidal-stream power resources, the momentum sink-TOC method was implemented in two depth-average, complex hydrodynamic models. The first numerical scheme simulates SSF, the second solves RVF.

2. Modelling approach

2.1. Smooth and slow flows

Two-dimensional shallow water equations (2D-SWE) are used to describe the evolution of tidal-streams through a tidal channel. The governing equations used to analyse SSF, characterised by small Froude numbers, consider an inviscid flow, neglect Coriolis force, and omit wind forcing. They are given by the depth-integrated continuity equation (Eq. (1)) and momentum equations, x-component is presented (Eq. (2)); a similar expression was used for y-component.

$$\frac{\partial \zeta}{\partial t} + \frac{q_x}{\partial x} + \frac{q_y}{\partial y} = 0 \tag{1}$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial \left(\frac{\beta q_x^2}{H}\right)}{\partial x} + \frac{\partial \left(\frac{\beta q_x q_y}{H}\right)}{\partial y} = -gH\frac{\partial \zeta}{\partial x} - \frac{g q_x \sqrt{q_x^2 + q_y^2}}{H^2 C_e^2} - \frac{F_{Tx}}{\rho} \tag{2}$$

where q_x=UH and q_y=VH represent depth-integrated velocity flux component in the x- and y-direction; t stands for time and β is the momentum correction factor for non-uniform vertical velocity profile. The surface elevation change with respect to mean water depth h is represented by ζ, where total water depth is $H = h+\zeta$. Bed shear stress is a function of Chezy roughness coefficient (C_e) and gravity (g). In this paper a small bottom drag is used ($C_d = 0.0025$) where $C_e = \sqrt{g/C_d}$.

Solution to SSF was approximated with ADI-TOC model, which is based on the Integrated Velocity And Solute Transport (DIVAST) model. ADI-TOC uses an Alternating Direction Implicit (ADI) scheme which is computationally more economical than RVF solvers [5].

2.2. Rapidly varying flows

Rapidly varying flows analysis required the conservative form of 2D-SWE to simulate strong gradients produced by power extraction within the flow. This representation of the equations ensures conservation of mass and momentum after discretisation and consequently, preserves the correct numerical solution of strong gradients (shocks) presented in the velocity and elevation fields [4]. Conservative form of 2D-SWE is obtained by treating H, q_x, and q_y as independent functions. The resultant system of equations is re-written as two one-dimensional hyperbolic equations [5], which are solved by TVD-TOC model. This model combines MacCormack and symmetric Total Variation Diminishing (TVD) schemes and it applies a shock-capturing technique to solve discontinuities in the flow. This efficient scheme was further optimised by incorporating parallel computing.

2.3. Turbine representation

The thrust force applied by the turbine on the stream was incorporated as an external force F_T in the momentum equations. In this way, thrust force is directly responsible of head drop and velocity changes produced by power extraction. In the case of x-component of momentum equation, the axial thrust per unit grid is:

$$F_{TX} = \frac{1}{2} A_x C_T U^2 \tag{3}$$

C_T *is a* thrust coefficient, and A_X is the turbine area projection on the *x*-direction. A similar expression is used for *y*-component. The momentum sink-TOC method was used to compute the thrust force. Computation of a non-constant thrust coefficient C_T required the selection of a wake induction factor (α_4) and β_4: $C_T = \beta_4^2 - \alpha_4^2$. Factor α_4 is an indicator of turbine's porosity or turbine's drag ($1 > \alpha_4 > 0$) [1]; optimum turbine performance is assumed by setting $\alpha_4 = 1/3$. Factor β_4 indicates the rate of velocity increase bypassing a turbine ($\beta_4>1$), it corresponds to a physical admissible root of a quartic polynomial [2]. Herein, the root was identified numerically with an Eigenvalue method.

2.4. Domain and turbine array

A steady tidal-stream forced by a semidiurnal tide through an idealised narrow channel, connecting two large basins was simulated. The length (L) and width (W) of the channel are 12 and 3 km, respectively. The water depth is relatively deep and constant at 40 m. The simulations commence from quiescent initial conditions and the amplitude of the incident standing wave ramped-up over two tidal periods. The domain size is large enough to ensure boundary conditions do not influence the power extraction dynamics. Flow conditions reached at the eighth tidal cycle are consistent with conditions at fourth tidal cycle, therefore the short period is reported. This layout enables to treat the tidal-stream as a bounded flow.

3. Tidal-stream resource assessment in a channel

LMAD-OCH theory enables the definition of turbine's thrust force (Eq. (3)) and power removed by the turbine (Eq. (4)) in terms of turbine's near-field changes produced by power extraction. These changes are parametrised by β_4, α_4, Δh, and turbine velocity coefficient (α_2).

$$P = \frac{1}{2}\rho U^3 A C_p \quad (4)$$

$$\alpha_2 = \frac{2(\beta_4 + \alpha_4) - (\beta_4 - 1)^3 (\mathrm{B}\beta_4^2 - B\beta_4\alpha_4)^{-1}}{4 + (\beta_4^2 - 1)(\alpha_4\beta_4)^{-1}} \quad (5)$$

where A stands for turbine swept area; in the case of ADI and TVD, it corresponds to the turbine cumulative area per grid cell and has two components (A_X, A_Y). The power coefficient $C_P = \alpha_2(\beta_4^2 - \alpha_4^2)$ depends on α_2, this coefficient indicates velocity reduction prior passing through the turbine. It also shows that power extraction dynamics is a function of three parameters sets: blockage ratio (B), β_4, and α_2 or α_4.

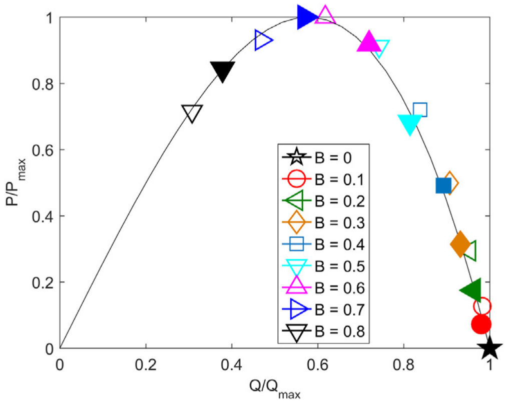

Fig. 1. Normalised maximum power removed by the turbines against normalised maximum flow rate for B increasing values. TVD (unfilled-markers), ADI (filled-markers), and analytical solution (continuous-line).

Momentum extracted by the turbines produces a free stream flow reduction throughout the channel as turbines increase the total drag in a channel. This effect is evident in the normalised powers P (Eq. (4)) and normalised flow rates Q obtained from TVD and ADI (Fig. 1). The variation in B produces a trend consistent with the analytical solution reported by Garrett and Cummins [6], and Sutherland et al. [7]. The trend indicates: (i) a maximum flow rate and null power extraction at natural-state ($B = 0$), (ii) the existence of an optimal blockage ratio that extracts a maximum power P_{MP}, and (iii) the reduction of power extraction for subsequent blockage ratio increases due to flow choking.

In the case of TVD, P_{MP} corresponds to $B = 0.6$, meanwhile ADI reports $B = 0.7$. The smaller blockage ratio required by TVD to reach maximum power agrees with Draper et al. [2]. Additionally, lower blockage ratios to reach P_{MP} are reported in advection-dominated flows (Draper et al. [2]). These types of flows are not completely balanced by bed friction drag and consequently, experience important flow advection. Semi-narrow, long, and deep channels such as the study are inclined to present flows with such characteristics. Advection-dominated flows are likely to be more accurately simulated by an RVF solver as strong gradients presented at the entrance (exit) of the channel are better approximated by this scheme.

Flow rate reduction simulated by the models is an indicator of the solution procedure accuracy implemented by ADI and TVD. The analytical solution of Sutherland et al. [7] indicates that P_{MP} can be reached with an optimal blockage ratio, which in turn is associated with ≈40% flow rate reduction. Consequently, if the blockage ratio required to reach P_{MP} is small, the flow reduction occurs at a faster rate. This situation is observed in TVD's results in Fig. 1. Conversely, if the blockage ratio required to reach P_{MP} is large, then flow reduction take places at a slower flow rate; this is the case of ADI. As the TVD model better simulates power extraction and flow rate reduction than ADI, the larger blockage ratio reported by ADI ($B = 0.7$) indicates that SSF solvers underestimates flow rate reduction produced by power extraction.

3.1. Head drop across an array and turbine efficiency

Head drops across the array were obtained from water depth differences between fence's upstream and downstream locations. Additionally, analytical solutions of head drop derived from LMADT-OCH were calculated by solving a cubic polynomial. Head drop consideration in the tidal-stream power extraction indicates that marine turbine extracts potential energy from the flow, rather than kinetic energy [1]. Coefficients of the polynomial are function of parameters F_r, B, and C_T which were obtained from TVD model as this scheme solves more accurately the flow field velocities reductions and power extraction. Time-averaged Δh obtained from ADI and TVD are compared with time-averaged analytical solution in Fig. 2(a). It indicates that increasing B produces larger Δh; in addition, it is observed that ADI solution is more consistent with the analytical solution. This result suggests that when power extraction is taken from bounded flows, where energy dissipated is mainly due to the turbine-wake mixing, the head drop can be estimated with an SSF solution scheme. Identification of head drop enable turbine-efficiency calculation, which indicates turbine performance and corresponds to the ratio of power removed by the turbine to total power extracted from the tidal-stream. For small Froude numbers: $F_r^2\,(1 - {}^{\Delta h}/_{h}) \ll 1$, a satisfactory approximation of the efficiency is given by $\eta \approx \alpha_2(1 - {}^{\Delta h}/_{2h})$. Time-averaged turbine efficiencies obtained from

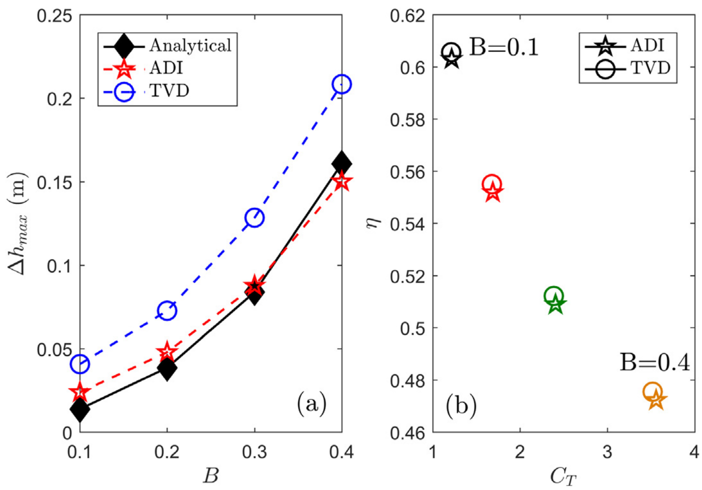

Fig. 2. Effect of blockage ratio on maximum water drop (a) and turbine-efficiency (b).

both ADI and TVD schemes for increasing B are plotted against time-averaged C_T (Fig. 2(b)). Gradual η reduction with the increase of both B and C_T indicates that more energy is lost during turbine-wake mixing. Similar turbine efficiencies are obtained from both models, however TVD results indicates slightly larger magnitudes due to larger Δh simulated by the scheme.

3.2. Power analysis

Tidal-stream resource assessment is performed as a post-processing simulation step. Based on LMAD-OCH analytical model, the identification of Δh and η allow the estimation of further power metrics such as total power extracted by the turbines P_T (Eq. (6)), power removed in terms of turbine efficiency and available for electrical generation P_* (Eq. (7)), and power dissipated by turbine wake mixing P_W (Eq. (8)).

$$P_T = \rho g U \frac{A}{B} \Delta h \left(1 - F_r^2 \frac{1 - \Delta h/2h}{(1 - \Delta h/h)^2}\right) \tag{6}$$

$$P_* = \eta P_T \tag{7}$$

$$P_\mathrm{W} = P_T(1 - \eta) \tag{8}$$

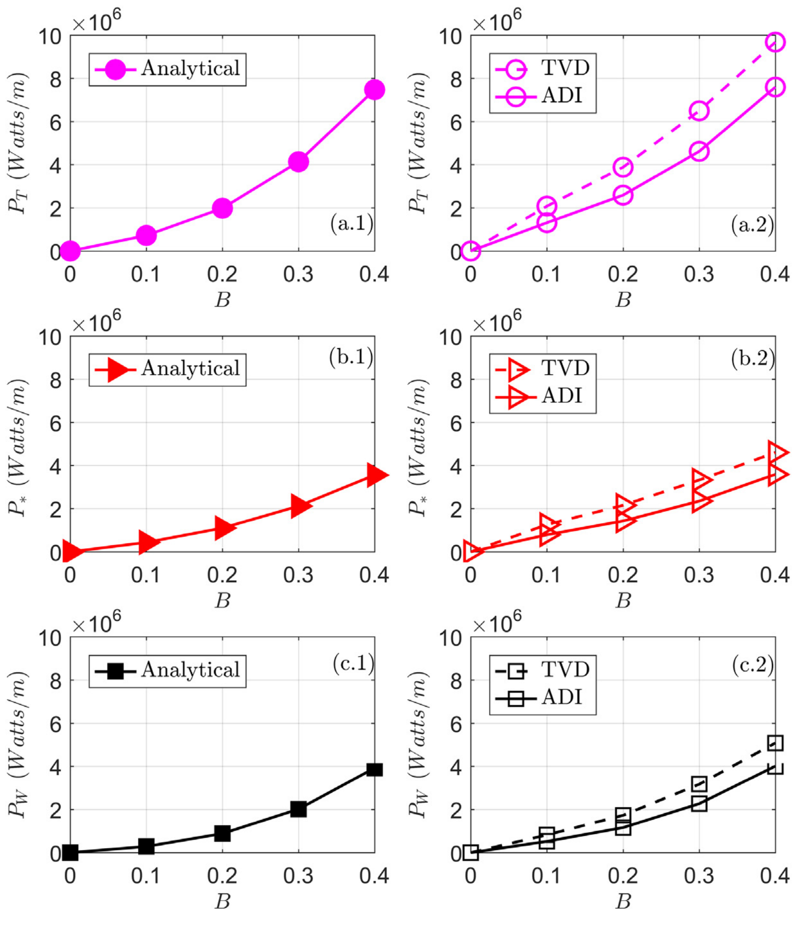

Fig. 3. Effect of blockage ratio on P_T (a), P_* (b), and P_W (c). Solutions from analytical model (filled markers), TVD (dash-line), and ADI (continuous-line).

Analytical power metrics obtained using analytical Δh were compared with solutions from both models. Time-averaged P_T estimated using the analytical and numerical calculations of Δh are presented in Fig. 3(a). Analytical and numerical solutions indicate a larger power extraction with increasing B. P_T is a function of head drop and as ADI approximates more accurately Δh across a tidal fence, the solutions provided by SSF solver are more consistent with P_T analytical solutions. Meanwhile, Δh overestimation reported by TVD is responsible of larger P_T magnitudes reported by RVF scheme. Power metrics P_* and P_W depend on the turbine-efficiency and head drop. However, as η solutions obtained from the models are similar, the head drop across an array explains P_* and P_W solutions. Time-averaged analytical and numerical solutions of P_* (Fig. 3(b)) and P_W (Fig. 3(c)) indicate that as ADI solves better Δh; therefore, P_* and P_W are more accurately simulated by an SSF solver.

4. Conclusions

Marine turbine energy capture simulated with momentum sink-TOC method enables the calculation of a non-constant trust force, which relates turbine operating conditions to the momentum extracted. Parametrisation of changes within turbine's near-field due to power extraction enables calculation of head drops across an array and turbine efficiencies. Assessment of bounded flow scenarios with SSF and RVF solvers indicate that both models produce similar turbine-efficiencies for increasing B's. An accurate approximation of water drop and turbine efficiency are necessary to correctly estimate P_T, P_* and P_W. The calculation of these metrics represents an advantage over conventional methodologies to evaluate the resource. Energy resource assessment for bounded flows are better performed with an SSF solver, because head drops were more accurately simulated by this scheme. Importantly, tidal-stream energy resource evaluation with a tidal fence indicate that a computationally economical pre-assessment can be adequately performed using widely available SSF solvers However, SSF solvers underestimate velocity reductions due to power extraction and must be used with caution.

Acknowledgements

The authors would like to thank to Science Foundation Ireland (SFI), Ireland, Centre for Marine Renewable Energy Ireland (MaREI), Ireland, and the Irish Centre for High-End Computing (ICHEC) for the provision of computational facilities and support.

References

[1] Houlsby G, Vogel C. The power available to tidal turbines in an open channel flow. Proc Inst Civ Eng Energy 2017;170:12–21.
[2] Draper S, Houlsby GT, Oldfield MLG, Borthwick AGL. Modelling tidal energy extraction in a depth-averaged coastal domain. IET Renew Power Gener 2010;4(6):545.
[3] Serhadlioglu S, Adcock TAA, Houlsby GT, Draper S, Borthwick AGL. Tidal stream energy resource assessment of the anglesey skerries. Int J Mar Energy 2013;3–4:e98–111.
[4] Liang D, Falconer RA, Lin B. Comparison between TVD-maccormack and ADI-type solvers of the shallow water equations. Adv Water Resour 2006;29(12):1833–45.
[5] Flores Mateos L, Hartnett M. Depth average tidal resource assessment considering an open channel flow. In: Soares Guedes C, editor. Advances in renewable energies offshore: Proceedings of the 3rd international conference on renewable energies offshore (RENEW). Taylor & Francis Group; 2018, p. 10.
[6] Garrett C, Cummins. The power potential of tidal currents in channels. Proc R Soc Ser A Math Phys Eng Sci 2005;461(2060):2563–72.
[7] Sutherland G, Foreman M, Garrett C. Tidal current energy assessment for Johnstone strait, Vancouver island. Proc Inst Mech Eng A 2007;221(2):147–57.