MODELLING OF HYDROKINETIC TURBINES AT DIFFERENT LENGTHSCALES

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INTRODUCTION

To fully understand the performance of tidal stream turbines for the development of ocean renewable energy, a range of computational models is required. We review and compare results from several models of horizontal axis turbines at different length scales. Models under review include blade element momentum theory (BEMT), blade element actuation disk RANS CFD (BEM-CFD), blade resolved moving reference frame, and coastal models based on the shallow water equations. A longer version of this abstract is contained in the open access journal paper by Masters et al. [1]

Conventional tidal renewable energy devices take the form of an axial flow turbine using hydrofoils that generate lift and drag. We may regard the torque that drives the rotation of the turbine as a function of the hydrodynamic forces that arise due to relative motion between the fluid and the rotating blades. Describing this relative motion, and thereby estimating the hydrodynamic forces, is therefore the primary requirement of a numerical scheme that models a tidal stream turbine (TST). One approach is to utilise a moving reference frame containing the rotating turbine blades, which we describe in this paper. More computationally efficient schemes treat the rotor as an actuator disk, blade element disk or actuator line. Here, we focus on the blade element disk approach, which we refer to as BEM-CFD (Blade Element Momentum-CFD). Finally, the least computationally-intensive numerical scheme is a blade element momentum theory (BEMT) approach, widely used for analysis of propellers and other rotors, where the flow field is assumed and the computation reduces to a 1D treatment of the blade elements, comparing tabulated lift and drag coefficients with axial and rotational induction factors.

The BEMT scheme is computationally very fast (20 minutes) and can be used to study in detail transient effects, such as the effects of waves and rotor control strategies. By contrast a TSR sweep in the BEM-CFD model takes around 5 days on a 32 core cluster. CPU times for coastal area models vary significantly based on the scale and resolution of the scenario being investigated.

CFD models can be used to investigate the near field: wake characteristics, recovery and interaction can all be modelled. Larger scale changes can be determined using coastal area models which can predict changes over hundreds of kilometres with much lower spatial resolution.

BEMT

The principle of the BEMT approach [2], is to reconcile two different models: a blade element (BE) model that treats the turbine as a collection of foil sections generating lift and drag, and a momentum theory (MT) model that treats the turbine as a series of annular stream tubes that modify velocity and swirl. Our BEMT code [3] incorporates several extensions to the classical theory, including tip/hub losses, high induction effects [4] and the ability to model an arbitrary inflow. Experimental results have already been published for three turbines: Cardiff/Liverpool [5-7]; IFREMER [8]; and Manchester [9]. All rotors have a three-bladed configuration, and good agreement between experiment and BEMT is shown in [1]. BEMT results for the IFREMER turbine are compared to experimental and CFD results in Figure 1.

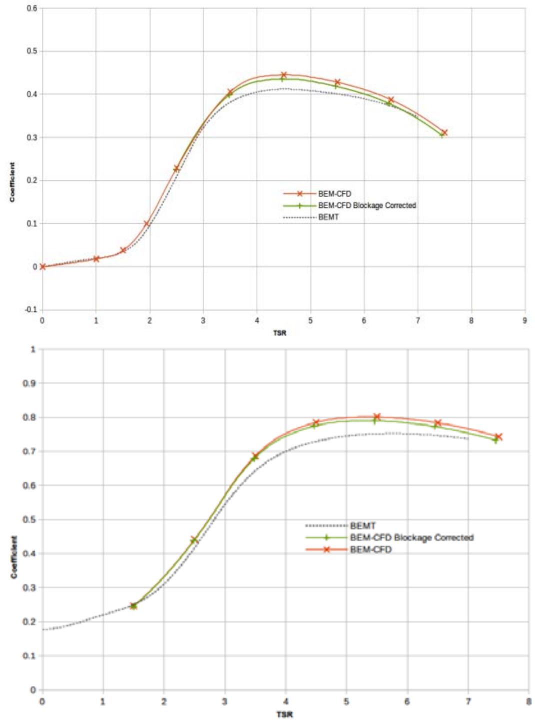

FIGURE 1. COMPARISON OF IFREMER ROTOR RESULTS FOR CP (COEFFICIENT OF POWER) AND CFA (COEFFICIENT OF AXIAL THRUST) BETWEEN BEM-CFD AND BEMT FOR A RANGE OF TSR'S. BLOCKAGE CORRECTED BEM-CFD RESULTS ARE INCLUDED FOR REFERENCE.

CFD AND BEM-CFD

CFD models of turbines normally use RANS [10, 11] or LES [12] with a blade resolved geometry (BRG) moving mesh to account for blade rotation. An alternative computationally efficient method is the BEM-CFD model [13-15] where the BEM method is used to model the turbine, and CFD elsewhere in the domain, thus giving us a time-averaged estimate of performance and the turbine wake, allowing study of arrays [16, 17]. To show the benefit of the approach, BEM-CFD is validated against CFD and experiments. The rotor design and Fluent CFD model was provided by Cardiff University [5] and scale tested at Liverpool [5-7]. It has a 10m diameter turbine in a rectangular domain with 3.086 m/s uniform inlet.

Rather than representing the geometry of the turbine directly, the equivalent BEM-CFD model treats the rotor as a momentum source/sink in the domain and the specification of the FX-63-137 blade is used to reproduce the chord, twist, lift and drag for the BEM-CFD model [1]. Both models employ a standard finite volume approach with a k-ε turbulence model.

In Figure 2, we compare predictions of velocity deficit at five diameter (5D) intervals behind the turbine. We see that the models agree well throughout most of the wake. The results also show that the wake shape for the BEM-CFD method is symmetric, while the BRG method's wake is slightly asymmetric. Figure 3 shows the velocity deficit and the turbulent kinetic energy for each of the models.

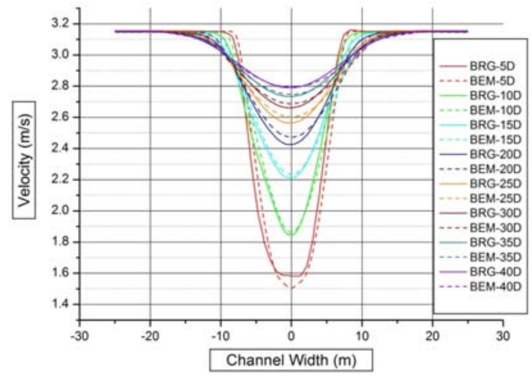

FIGURE 2. COMPARISON OF THE VELOCITY DEFICIT IN THE ROTOR WAKE FROM BEM-CFD AND BLADE-RESOLVED GEOMETRY (BRG) MODELS AT A RANGE OF DOWNSTREAM LOCATIONS

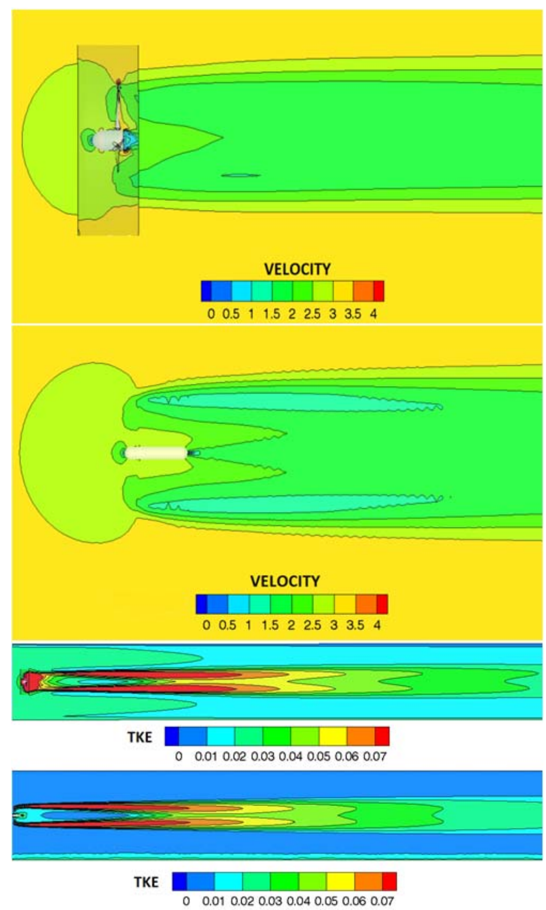

FIGURE 3. COMPARISON OF THE VELOCITY DEFICIT (TOP RIGHT AND LEFT) AND TURBULENT KINETIC ENERGY FOR BLADE-RESOLVED GEOMETRY (BRG) (MIDDLE) AND BEM-CFD (BOTTOM) IN THE CARDIFF 10M ROTOR WAKE.

In addition, a comparison of BEM-CFD and BEMT methods is also conducted using the rotor geometry from the IFREMER experimental study [8]. Figure 1 demonstrate the coefficient of power and axial thrust. The results show that BEMT under predicts power in comparison to BEM-CFD. This under-prediction is largest near optimum, with the model predictions varying by 5.4%. In comparing the BEMT, BEM-CFD and experimental results, it is important to bear in mind the effects of blockage and how this differs between the three cases. BEMT results always reflect a theoretically perfect blockage-free state, whereas both experiments and CFD can introduce flow blockage (flume walls for experiment, domain boundaries for CFD). The BEM-CFD simulations omitted the mast on which the turbine was mounted [8] for reasons of computational cost. The experimental measurements included the drag on this mast, which explains the offset in thrust values.

COASTAL AREA MODELLING

While CFD and BEMT approaches are focused very much on the turbine itself, computational limitations mean that different techniques are required for the modelling of larger-scale impacts or for long time period transient simulations. Coastal area models are therefore used, which typically solve the shallow water equations in two or three dimensions. Coastal scale modelling typically investigates available resource [18] or the impacts of energy extraction on the wider environment for array or inter-array scenarios.

Impacts on the hydrodynamic regime can be observed over a much larger area than covered by CFD for tidal barrages and stream turbines [19, 20]. Researchers have also investigated impacts on sediment transport [21-23], changes to currents impacting the wave climate [24, 25] and water quality [26]. A variety of methods have been used for the implementation of turbines in coastal array models: in two-dimensional models turbines are often included as bottom friction [22, 27-29]. In three-dimensional models better vertical velocity profiles are achieved with a sink term [23]. A review of the commonly used methods is presented in [30]. Some studies have also included turbulence [31].

Currently few turbines are installed in the real world and therefore it is not currently possible to conduct model – measurement comparisons at scales relevant to coastal area models. Therefore, a model-model comparison between BEM-CFD and a coastal area model, was undertaken using a simplified case of a fence of 6 turbines at an idealised headland. The scenario was based on [32] and details of the model setup are given in [17] and [1]. The BEM-CFD model was that described above and the coastal area model used was MIKE3 [33], chosen because it is a commercial piece of code regularly used in renewable energy applications. MIKE3 has an inbuilt turbine tool based on actuator disk theory [25], which is implemented as a momentum sink.

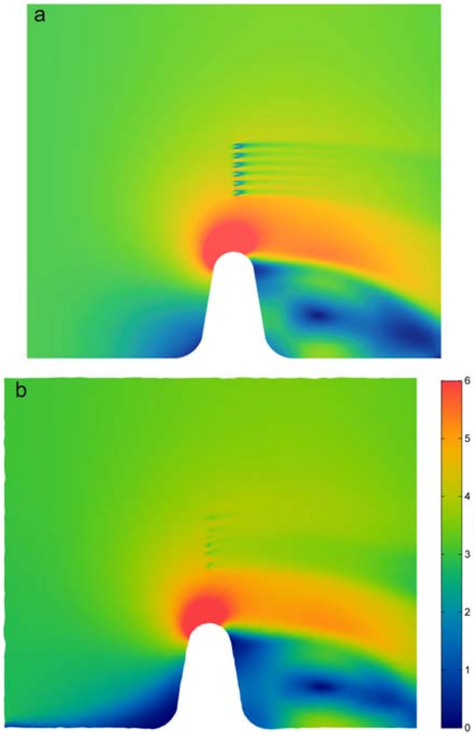

FIGURE 4. HORIZONTAL FLOW FIELDS FOR THE HEADLAND FENCE CASE: THE IMAGES SHOW VELOCITY MAGNITUDE AT HUB HEIGHT FROM (A) THE BEM-CFD MODEL AND (B) THE COASTAL AREA MODEL. FLOW IS FROM LEFT TO RIGHT IN THE IMAGES.

Figure 4 shows the velocity field at hub height for both simulations. Clearly the BEM-CFD model resolves the turbine wakes in much greater detail, however in the far field flows are similar. Figure 5 shows the difference in mesh speeds between the two cases. Flow velocities in the far-upstream and offshore of the turbine fence can be seen to be very similar. Flows between the headland and the turbine fence are slightly lower for the coastal area model than for the BEM-CFD. Figure 5 shows that coastal area model has very slightly lower velocities in front of the turbine for some areas. This may in part be due to the different treatment of pressure in the two models. Additionally, the triangular shape of the differences suggest mesh resolution may be a contributing factor. Velocities are lower in the gaps between the turbines for the coastal area model. In the near wake, velocities are generally higher for the coastal area model.

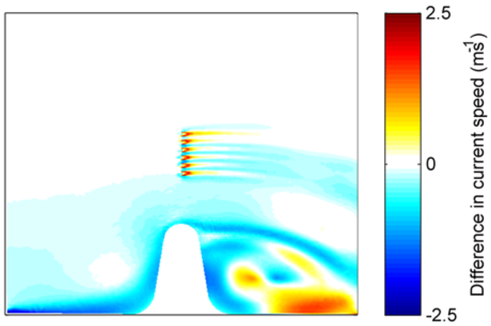

FIGURE 5. DIFFERENCES IN HORIZONTAL VELOCITY MAGNITUDE FOR THE HEADLAND FENCE CASE; NEGATIVE VALUES INDICATE THAT VELOCITY MAGNITUDE IS LOWER IN THE COASTAL AREA MODEL.

CONCLUSIONS

Computer modelling has always been a compromise between three issues: the numerical description, computational resources and experimental validation. We have presented here several numerical schemes to describe the extraction of useful energy from a tidal turbine and the interaction that it has with the flow. It is clear that the correct choice of scheme is not always obvious, and depends on the physical scale where answers are required. It is clear that reasonable characterisation of lab-scale flows can be achieved with good instrumentation, and the experiments used for validation can be replicated with reasonable accuracy using BEMT, BEM-CFD and BRG approaches. However, real flows have a very high uncertainty in the characterisation of the problem and care should be taken when making comparisons to real turbines in real channels. Comparison between CFD and coastal area models is less clear due to the greater differences in terms of scale, mesh resolution and temporal discretisation.

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REFERENCES

1. A Comparison of Numerical Modelling Techniques for Tidal Stream Turbine Analysis, I. Masters I., A.J. Williams, T.N. Croft, M. Togneri, M. Edmunds, E. Zangiabadi, I. Fairley, H. Karunarathna, Energies, (8) 2015, 7833-7853
2. T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, Wind Energy Handbook, Wiley (2001)
3. I. Masters, J.C. Chapman, J.A.C. Orme and M.R. Willis, "A robust blade element momentum theory model for tidal stream turbines including tip and hub loss corrections", Proc. IMarEST Pt A – J. Marine Engin. Tech., 10:25-25 (2011)
5. Mason-Jones A. 2010. Performance assessment of a horizontal axis tidal turbine. PhD Thesis, Cardiff University, UK.
4. J.C. Chapman, I. Masters, M. Togneri and J.A.C. Orme, "The Buhl correction factor applied to high induction conditions for tidal stream turbines", Renew. Energy, 60:472-480 (2013)
6. S.C. Tedds, I. Owen and R.J. Poole, "Near-wake characteristics of a model horizontal axis tidal stream turbine", Renew. Energy, 63:222-235 (2014)
7. T.A. de Jesus Henriques, S.C. Tedds, A. Botsari, G. Najafian, T.S. Hedges, C.J. Sutcliffe, I. Owen and R.J. Poole, "The effects of wave-current interaction on the performance of a model horizontal axis tidal turbine", IJ. Marine Energy, 8:17-35 (2014)
8. P. Mycek, B. Gaurier, G. Germain, G. Pinon and E. Rivoalen, "Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: One single turbine", Renew. Energy, 66:729-746 (2014)
9. E. Fernandez-Rodriguez, T.J. Stallard, P.K. Stansby, "Experimental study of extreme thrust on a tidal stream rotor due to turbulent flow and with opposing waves", J. Flu. Struc., 51:354-361 (2014)
10. D. O'Doherty, A. Mason-Jones, C. Morris, T. O. O'Doherty, C. Byrne, P. Prickett and R. Grosvenor, "Interaction of marine turbines in close proximity", 9th EWTEC (2011), Southampton, UK
11. A. Mason-Jones, D. O'Doherty, C. E. Morris, T. O'Doherty, C. Byrne, P. W. Prickett, R. I. Grosvenor, I. Owen, S. Tedds et al., "Non-dimensional scaling of tidal stream turbines", Energy 44(1):820-829 (2012)
12. I. Afgan, J. McNaughton, S. Rolfo, D. D. Apsley, T. Stallard and P. Stansby, "Turbulent flow and loading on a tidal stream turbine by LES and RANS", Int. J. Heat Fluid Flow 43:96-108 (2013)
13. M. Willis, I. Masters, S. Thomas, R. Glalie, J. Loman, A. Cook, R. Ahmadian, R. Falconer, B. Lin, G. Gao et al., "Tidal turbine deployment in the

Bristol Channel: a case study", Proc. ICE-Energy 163(3):93-105 (2010)
14. M. E. Harrison, W. M. J. Batten and A. S. Bahaj, "A blade element actuator disc approach applied to tidal stream turbines", OCEANS 2010 (2010), Seattle, USA
15. R. Malki, A. J. Williams, T. N. Croft, M. Togneri and I. Masters, "A coupled blade element momentum-computational fluid dynamics model for evaluating tidal stream turbine performance", Appl. Math. Model. 37(5):3006-3020 (2013)
16. Malki, Rami, Ian Masters, Alison J. Williams, and T. Nick Croft. "Planning tidal stream turbine array layouts using a coupled blade element momentum–computational fluid dynamics model." Renewable Energy 63 (2014): 46-54.
17. Edmunds, M., R. Malki, A. J. Williams, I. Masters, and T. N. Croft. "Aspects of tidal stream turbine modelling in the natural environment using a coupled BEM–CFD model." International Journal of Marine Energy 7 (2014): 20-42.
18. Lewis, M., Neill, S. P., Robins, P. E., & Hashemi, M. R. (2015). Resource assessment for future generations of tidal-stream energy arrays. Energy, 83, 403-415
19. R. Ahmadian, R. Falconer and B. Bockelmann-Evans, "Far-field modeling of the hydro-environmental impact of tidal stream turbines", Renew. Energy 28:107-116 (2012)
20. R. Ahmadian and R. A. Falconer, "Assessment of array shape of tidal stream turbines on hydro-environmental impacts and power output", Renew. Energy 44:318-327 (2012)
21. A C. Chatzirodou and H. Karunarathna, "Impacts of tidal energy extraction on sea bed morphology", 34th International Conference on Coastal Engineering, (2014), Seoul, South Korea
22. P. E. Robins, S. P. Neill and M. J. Lewis, "Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes", Renew. Energy 72:311-321 (2014)
23. I. Fairley, I. Masters, H. Karunarathna, "The cumulative impact of tidal stream turbine arrays on sediment transport in the Pentland Firth". Renew. Energy 80:755-769 (2015)
24. M. R. Hashemi, S. P. Neill, P. E. Robins, A. G. Davies and M. J. Lewis, "Effect of waves on the tidal energy resource at a planned tidal stream array", Renew. Energy 75:626-639 (2015)
25. I. Fairley, R. Ahmadian, R. A. Falconer, M. R. Willis, I. Masters, "The effects of a Severn Barrage on wave conditions in the Bristol Channel", Renew. Energy 68:428-442 (2014)
26. M. Kadiri, M. R. Hashemi, B. Bockelmann-Evans, W. Rauen and R. Falconer, "A review of the potential water quality impacts of tidal renewable energy systems", Renew. Sust. Energy Rev. 16:329-341
27. R. Martin-Short, J. Hill, S. C. Kramer, A. Avdis, P. A. Allison and M. D. Piggott, "Tidal resource extraction in the Pentland Firth, UK: Potential impacts on flow regime and sediment transport in the Inner Sound of Stroma", Renew. Energy 76:596-607 (2015)
28. Vogel, C. R., Willden, R.H.J. & Houlsby, G.T. A correction for depth-averaged simulations of tidal turbine arrays. In Proc. 10th EWTEC, Aalborg, Denmark. (2013)
29. Nishino, Takafumi, and Richard HJ Willden. "The efficiency of an array of tidal turbines partially blocking a wide channel." Journal of Fluid Mechanics 708: 596. (2012)
30. S. Baston, S. Waldman and J. Side, "Modelling energy extraction in tidal flows", MASTS Position Paper (2014)
31. T. Roc, D. Conley, D. Greaves, "Methodology of tidal turbine representation in ocean circulation model," Renewable Energy 51:448-464. (2013)
32. S.Draper, A. Borthwick, G. Houlsby, "Energy potential of a tidal fence deployed near a coastal headland," Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 371:1985 (2013)
33. DHI, MIKE 21 and MIKE 3 Flow Model FM - Hydrodynamic and Transport Module - Scientific Documentation. (2012).