Review of Dalhousie University's Past and Current Projects on Numerical Modelling of Tidal Turbines and Load Characterization

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I. Introduction

FROM its close location to the Bay of Fundy in Nova Scotia (Canada) and its focus on ocean-related research, Dalhousie University was naturally drawn to the provincial effort related to tidal energy. One particular area of research pursued by the Faculty of Engineering is related to tidal turbine behaviour in a tidal flow, and the resulting flow behaviour around and in the wake of such turbines.

This work has been performed numerically using the commercial software ANSYS CFX, building on experimental and numerical work done over the last two decades. Early experimental characterization of tidal turbines, mostly 3-bladed horizontal axis, were performed in tow tank and flume tank across the world, notably in Southampton (UK) [1], IFREMER (France) [2, 3], Naples (Italy) [4], Liverpool (UK) [5]. Numerical work was done assessing the overall power production and thrust generated using simpler approaches like the blade element momentum theory (BEMT) [6, 7], or actuator disks [8]. With increased computing power, more recent work has transitioned to fully resolved 3D computational fluid dynamics (CFD) simulations, sometimes coupled with a BEMT approach [9], or often using a shear stress transport (SST) approach [10, 11], detached eddy simulations [3, 12] or large eddy simulations [13].

Vertical axis turbines were also tested experimentally, notably in Japan (Darrieus type) [14] and numerical work was performed to understand their performance [15-18].

This short paper will present a review of the work done on the last decade on the numerical modelling of 3-blade horizontal axis turbines at Dalhousie University. This work looked at aspect of the modelling method, impact of Bay of Fundy representative flow conditions, the nature of the wake generated by a turbine, the interaction between turbines and elements related to the loading of blades.

II. Quasi Steady-State Approach

The initial project on numerical modelling at the Laboratory of Applied Multiphase Thermal Engineering (LAMTE) in the Department of Mechanical Engineering at Dalhousie started over a decade ago in 2013 when Mr. Nick Osborne started his MASc degree.

The focus of this initial project was to learn the required numerical method used at the time to model flow over a tidal turbine, and then look at the resulting wake from this turbine. The geometry of the Southampton turbine was used in the numerical work and for validation [19]. An SST turbulence model was used in conjunction with the quasi steady-state approach (frozen rotor) [20].

This first foray in the modelling pinpointed the importance of the geometry of the blades and turbine hub, as well as the mesh at the walls of the geometry, on the global power and thrust coefficient as defined in Eq. (1) and (2):

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

$$C_T = \frac{T}{\frac{1}{2}\rho A U^2} \quad (2)$$

As a good example, Fig. 1a) shows the numerical C_P obtained with the original geometry estimated from the Southampton turbine compared to the experimental results as a function of the tip speed ratio (TSR = $\omega R/U$) [10]. The difference between both curves is quite pronounced.

Continued work showed that the sharpness of the blade trailing edge geometry and mesh played a major role in the resulting lift force on the blade, varying by approximately 20% on the range of trailing edge roundness diameter studied [21]. Figure 1b) presents the updated C_P obtained after a thorough review of the geometry and mesh for the same system.

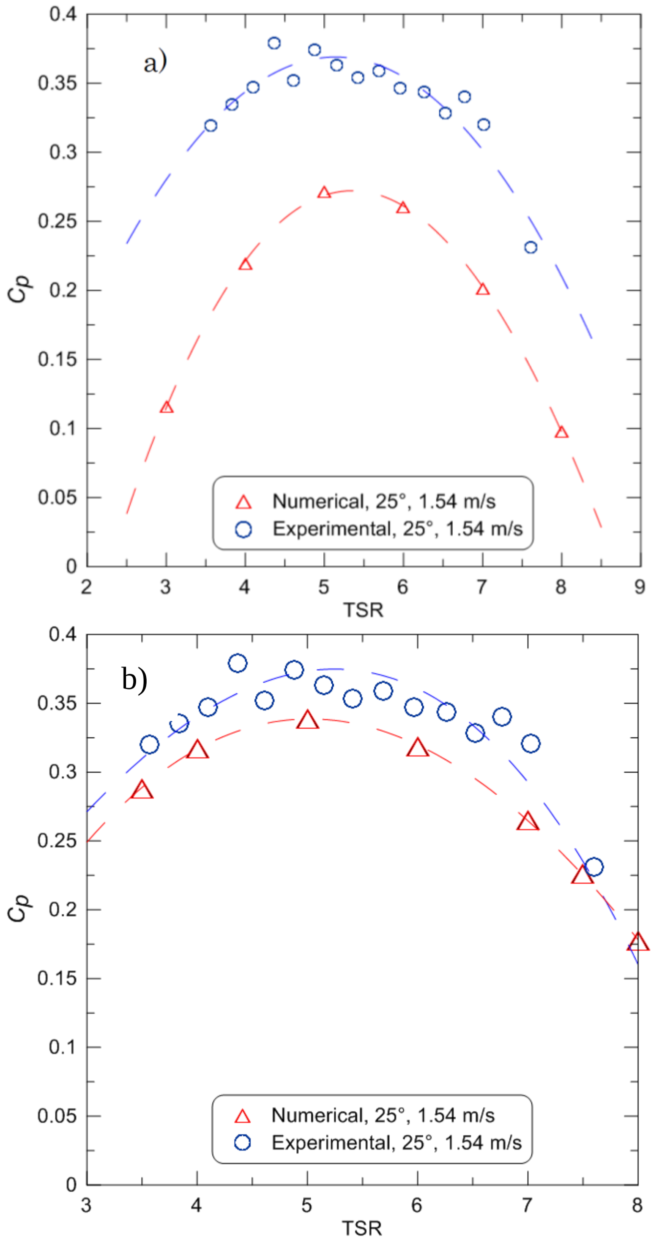

Fig. 1 Comparison of power coefficients as a function of the TSR between experimental results [19] and: a) initial numerical modelling from [10], and b) numerical modelling after a thorough impact of the geometry and meshing [21]. Note that the TSR range was reduced on b).

Through this work, the impact of the turbulence model (*k-ε*, *k-ω* and SST) on the wake was studied, so was the behaviour of the wake (using SST) was a function of the TSR value.

A PhD project between Dalhousie University and Strathclyde University (Scotland) was in progress during that time where the researchers studied a turbine using a different blade profile: NREL S814 [22]. This type of blade has a higher thickness to chord ratio.

The same numerical methodology applied previously was then applied to this new turbine, using the experimentally determined C_p and C_T for validation [23]. Figure 2 shows the comparison between the numerical C_p and the experimental ones for this new turbine, showing great agreement and providing a second validation of the numerical approach in terms of determining C_p and C_T.

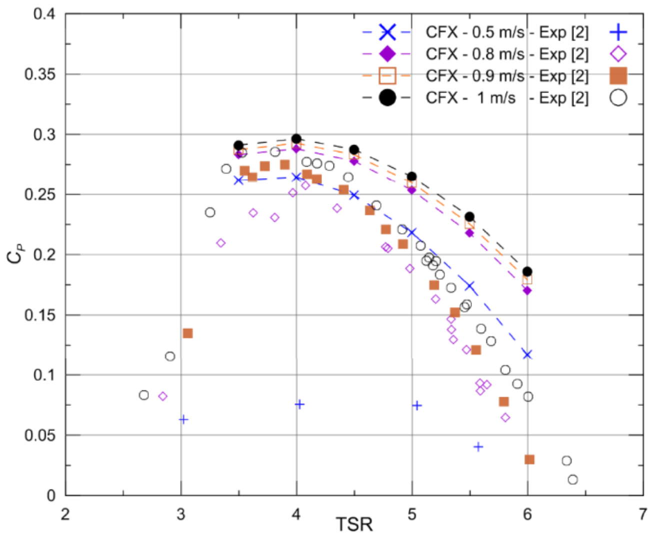

Fig. 2 Comparison of power coefficients as a function of the TSR between experimental results and numerical modelling for a turbine using NREL S814 blades [23].

Finally, results were also obtained with this method using the turbine geometry used at IFREMER in France [2], showing great agreement between the global turbine performance parameters [11]. Work on this turbine also compared to results obtained by using a fully transient approach (Section III).

III. Transient Approach

Following the presentation of work by the research group at Queen's University Belfast in 2014 [24] where results showed that a tidal turbine might produce up to 40% less energy in a transient tidal flow compared to a steady-state condition[1] (pushed by a boat at constant speed), the next project at the LAMTE focused on moving the numerical modelling to a fully transient approach.

The first project done used the validated model of the turbine with the NREL S814 blades and compared the C_p and C_T obtained under a steady-state 2.05 m/s inlet flow to a transient flow using a turbulent inlet condition representative of a Bay of Fundy tidal current that averages to 2.05 m/s (Fig. 3a) [25].

From Fig. 3b), results of this work concluded that the instantaneous value of C_p could vary by approximately ±25% around the steady-state C_p value at a TSR of 4 (best performance for this turbine as per Fig. 2). However, at the same TSR, the instantaneous thrust (C_T) on the turbine could vary by up to ±90% around the steady-state value (Fig. 3c).

The overall energy produced by the turbine under steady-state and transient operation over the 20 s of the simulation added up to the same amount, pointing to the issue in the work of Queen's University Belfast being on the measurement side, and not on the tidal flow and energy capture side of the turbine[1].

[1] It was determined, and presented at a conference in 2016, by the Queen's University Belfast Group that the 40% difference in energy production was due to a limitation in the Data Acquisition (DAQ) system, which was fixed.

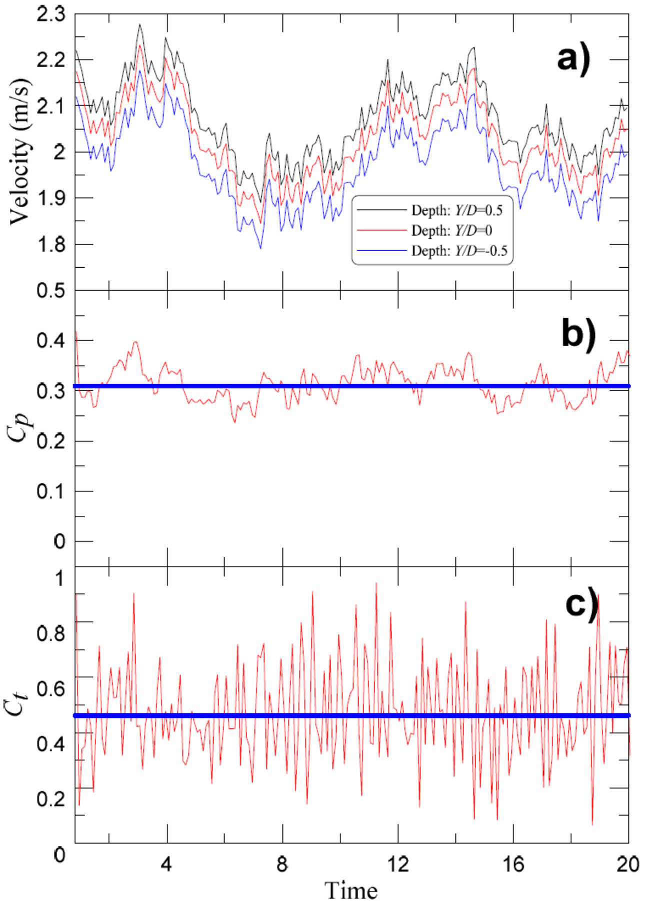

Fig. 3 a) Inlet velocity as a function of time for 3 different depths (Y/D = 0 corresponds to the hub height), b) C_P as a function of time, and c) C_T as a function of time. The time on the x-axis is in seconds (b) and c), blue line represents steady-state simulation results, red transient simulation results) [25].

The result of this work, when focusing on the thrust on the turbine, did show that under transient tidal flow conditions, the forces of the turbine and the blades would vary rapidly and by large amounts. This opened the door to the next step in the study (Section IV).

However, another transient study was performed to compare the nature of the turbine wakes obtained when using a quasi-steady (frozen rotor) or a transient numerical approach [11]. Using the model of the IFREMER turbine, it was also possible to compare the numerically calculated wake to the one measured experimentally by the researchers.

It was found that the wake obtained from the transient wake provided a more physically meaningful wake behaviour; see Fig. 4 that shows that the wake obtained from the transient approach preserves the imprint of the rotating turbine blades. However, this approach over predicted the velocity deficit in the wake compared to the quasi-steady results who were closer to the experimental ones, and within the experimental uncertainty.

IV. Transient Loading

The combination of transient simulations and using transient tidal flow inlet data pointed to the fact that the loading on the turbine will vary greatly. This should also

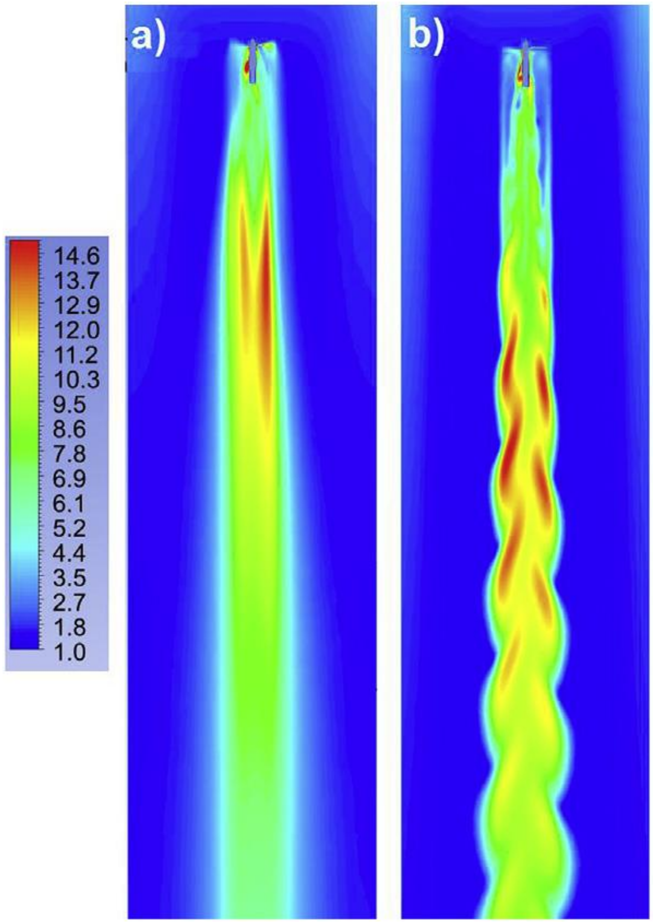

Fig. 4 Turbulence intensity on mid-horizontal plane with a a) quasi-steady, frozen rotor, approach, b) transient approach (snapshot at t = 80 s). TSR = 3.67. I_∞ = 3% and V_0 = 0.8 m/s [11].

be the case locally on the blades of a turbine. Therefore, the work continued using the NREL S814 blade geometry in collaboration with colleagues from ENSTA Bretagne (France). The initial work focused on the transient nature of the simulation and used a front turbine to generate a transient wake, from a constant inlet condition, that would flow over a second turbine positioned at a distance of 10 diameters (10*D*) behind the front one (see Fig. 5). The downstream turbine was either in-line with the upstream one, or move sideways by 0.5*D* or 1*D* relative to the upstream turbine.

Figure 6 presents the turbines C_T for a rotation period. When the two turbines are in line, the C_T goes down by approximately 45% but oscillates with an amplitude variation of 14%.

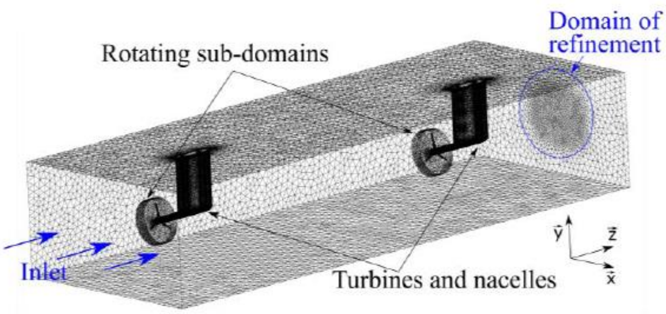

Fig. 5 Meshed model used to simulate the impact of a wake generated by a first turbine on the local blade loading of the downstream turbine [26].

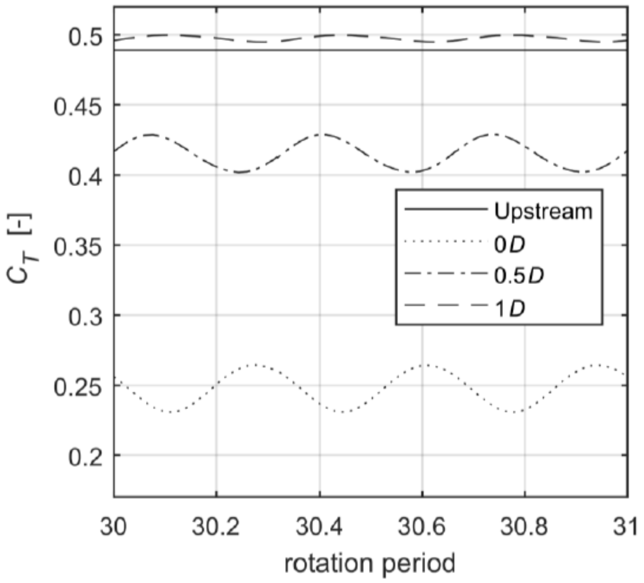

Fig. 6 Numerical C_T value over one rotation period at TSR = 4 for the upstream and downstream turbine as a function of the downstream turbine position [26].

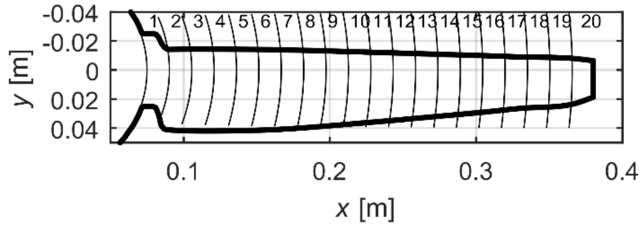

Fig. 7 Turbine blade sections for discrete local loading evaluations [27].

On the other hand, because of the flow displacement, the turbine positioned 1*D* sideways sees are higher C_T [26].

Interestingly, when determining the local and transient forces on blade sections through post-processing, it is found that the dimensionless local thrust coefficient (Eq. 3) varies greatly depending on the position of the downstream turbine and the local position on the blade [27].

$$C_{T_l} = \frac{T_l}{\frac{1}{2}\rho A_s U^2} \tag{1}$$

where T_l is the local load on a blade section and A_s is the area of this blade local section (Fig. 7).

Figure 8 presents an example of local loadings on four local sections of the blade in the case where the downstream turbine is positioned 0.5*D* sideways [28]. It can be observed that for sections in the further half of the blade, the local thrust coefficient varies by over 50% each rotation of the blade (the shaded area represents the amplitude of variation of the coefficient over a dozen rotations). The entirety of this work is not yet published but will be submitted soon [28].

V. Current and Future Work

Funding was secured in 2022 through the Ocean Frontier Institute and Canada's National Research Labs to expend on this transient loading work. The second author

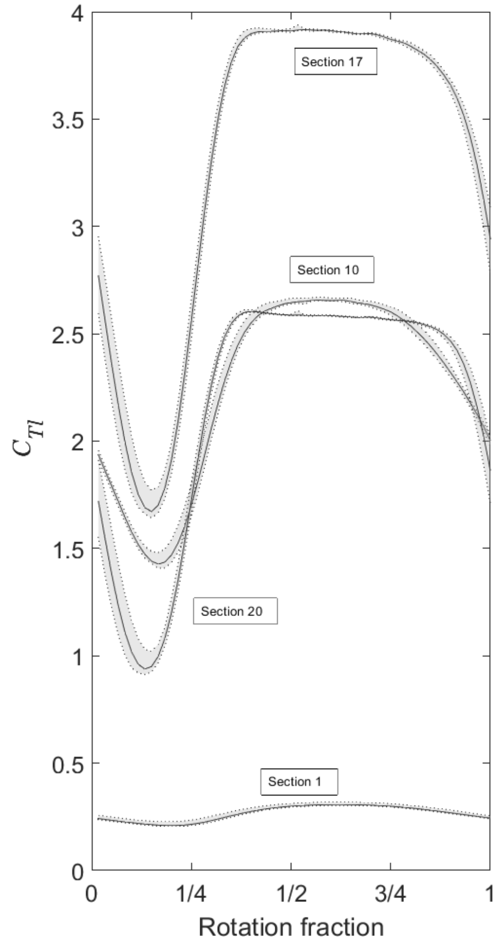

Fig. 8 Local thrust coefficient variation over a rotation period for four sections of the blade of the downstream turbine positions 0.5D sideways for both turbines operating at TSR = 4. Paper in preparation [28].

of this paper (A. Akinnibosun) was selected as a PhD candidate for this work. The main goal of this continued work is to combine the transient local blade load approach presented in Section IV to the real tidal flow inlet conditions approach used in Section III to determine local and transient load variations on turbine blades as a function of the transient inlet conditions that are representative of various tidal sites.

It is expected that the results of this work will benefit design and structural engineers that will be able to determine the time to failure by fatigue of their turbine blades.

Therefore, for this work, real and representative tidal flow data, obtained at frequency below 1 Hz, would be required as inlet boundary conditions. The researchers have access to such data from Dalhousie's colleagues in oceanography; data that was taken from regions around the Bay of Fundy. Discussions with NRC about the availability of such data from other tidal sites in Canada are underway.

The authors are open to discussions with other groups around the world that have and would be willing to share this type of local turbulent flow data from their tidal sites.

References

[1] W. M. J. Batten, A. S. Bahaj, A. F. Molland, and J. R. Chaplin, "Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines," *Ocean Engineering,* vol. 34, pp. 1013-1020, 2006.

[2] 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," *Renewable Energy,* vol. 66, pp. 729-746, 2014.

[3] T. Ebdon, M. J. Allmark, D. M. O'Doherty, A. Mason-Jones, T. O'Doherty, G. Germain, and B. Gaurier, "The impact of turbulence and turbine operating condition on the wakes of tidal turbines," *Renewable Energy,* vol. 165, pp. 96-116, 2021.

[4] D. P. Coiro, U. Maisto, F. Scherillo, S. Melone, and F. Grasso, *Horizontal Axis Tidal Current Turbine: Numerical and Experimental Investigations,* Seminar, Department of Aeronautical Engineering, University of Naples "Federico II", Civitavecchia, Italy, 2006.

[5] T. O'Doherty, A. Mason-Jones, D. M. O'Doherty, C. B. Byrne, I. Owen, and Y. X. Wang, "Experimental and Computational Analysis of a Model Horizontal Axis Tidal Turbine," in 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 2009, pp. 833-841.

[6] W. M. J. Batten, A. S. Bahaj, A. F. Molland, and J. R. Chaplin, "The prediction of the hydrodynamic performance of marine current turbines," *Renewable Energy,* vol. 33, no. 5, pp. 1085-1096, 2008.

[7] I. Masters, M. Willis, and J. A. C. Orme, "A robust blade element momentum theory model for tidal stream turbines including tip and hub loss corrections," *Journal of Marine Engineering and Technology,* vol. 10, no. 1, pp. 25-35, 2011.

[8] J. I. Whelan, J. M. R. Graham, and J. PeirÓ, "A free-surface and blockage correction for tidal turbines," *Journal of Fluid Mechanics,* vol. 624, pp. 281, 2009.

[9] I. Masters, R. Malki, A. J. Williams, and T. N. Croft, "The influence of flow acceleration on tidal stream turbine wake dynamics: A numerical study using a coupled BEM–CFD model," *Applied Mathematical Modelling,* vol. 37, no. 16-17, pp. 7905-7918, 2013.

[10] N. Osbourne, D. Groulx, and I. Penesis, "Three Dimensional Simulation of a Horizontal Axis Tidal Turbine - Comparison with Experimental Results." 8 p.

[11] T. Leroux, N. Osbourne, and D. Groulx, "Numerical study into horizontal tidal turbine wake velocity deficit: Quasi-steady state and transient approaches," *Ocean Engineering,* vol. 181, pp. 240-251, 2019.

[12] M. Faizan, S. Badshah, M. Badshah, and B. A. Haider, "Performance and wake analysis of horizontal axis tidal current turbine using Improved Delayed Detached Eddy Simulation," *Renewable Energy,* vol. 184, pp. 740-752, 2022.

[13] 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," *International Journal of Heat and Fluid Flow,* vol. 43, pp. 96-108, 2013.

[14] M. S. Shiono, K.; Kiho, S., "An Experimental Study of the Characteristics of a Darrieus Turbine for Tidal Power Generation," *Electrical Engineering in Japan,* vol. 132, no. 3, 2000.

[15] P. Marsh, D. Ranmuthugala, I. Penesis, and G. Thomas, "Performance Predictions of a Straight-Bladed Vertical Axis Turbine Using Double-Multiple Streamtube and Computational Fluid Dynamics Models," *The Journal of Ocean Technology,* vol. 8, pp. 18, 2013.

[16] Y. Li, and S. M. Calisal, "Modeling of twin-turbine systems with vertical axis tidal current turbines: Part 1 - Power output," *Ocean Engineering,* vol. 37, no. 627-637, pp. 11, 2010.

[17] Q. Sheng, S. S. Khalid, Z. Xiong, G. Sahib, and L. Zhang, "CFD simulation of fixed and variable pitch vertical axis tidal turbine," *Journal of Marine Science and Application,* vol. 12, no. 2, pp. 185-192, 2013.

[18] B. Yang, and C. Lawn, "Fluid dynamic performance of a vertical axis turbine for tidal currents," *Renewable Energy,* vol. 36, pp. 3355-3366, 2011.

[19] A. S. Bahaj, A. F. Molland, J. R. Chaplin, and W. M. J. Batten, "Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank," *Renewable Energy,* vol. 32, no. 3, pp. 407-426, 2007.

[20] N. Osbourne, "3D Modelling of a Tidal Turbine - A Numerical Investigation of Wake Phenomena," Mechanical Engineering, Dalhousie University, Halifax, 2015.

[21] N. Osbourne, D. Groulx, and I. Penesis, "3D Modelling of a Tidal Turbine - An Investigation of Wake Phenomena," in 11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France, 2015, 10 p.

[22] D. A. Doman, R. E. Murray, M. J. Pegg, K. Gracie, C. M. Johnstone, and T. Nevalainen, "Tow-tank testing of a 1/20th scale horizontal axis tidal turbine with uncertainty analysis," *International Journal of Marine Energy,* vol. 11, pp. 105-119, 2015.

[23] G. Currie, N. Osbourne, and D. Groulx, "Numerical Modelling of a Three-Bladed NREL S814 Tidal Turbine," in 3rd Asian Wave and Tidal Energy Conference (AWTEC), Singapore, 2016, 10 p.

[24] P. Jeffcoate, B. Elsaesser, T. Whittaker, and C. Boake, "Testing Tidal Turbines - Part 1: Steady Towing Tests vs. Tidal Mooring Tests," in International Conference on Offshore Renewable Energy, Glasgow (Scotland), 2014, 9 p.

[25] T. Leroux, N. Osbourne, J. M. McMillan, D. Groulx, and A. E. Hay, "Numerical Modelling of a Tidal Turbine Behaviour under Realistic Unsteady Tidal Flow," in 3rd Asian Wave and Tidal Energy Conference (AWTEC), Singapore, 2016, 10 p.

[26] V. Podeur, D. Groulx, and C. Jochum, "A Numerical Study of Transient Turbine Wake Interaction," in International Conference on Ocean Energy (ICOE) 2018, Cherbourg, France, 2018, 7 p.

[27] V. Podeur, D. Groulx, and C. Jochum, "Tidal Turbine Interaction Effect of Upstream Turbine Wake on Downstream Turbine," in 4th Asian Wave and Tidal Energy Conference (AWTEC), Taipei, Taiwan, 2018, 10 p.

[28] V. Podeur, L. Michaud, D. Groulx and C. Jochum, "Numerical Determination of Local Tidal Turbine Blade Loading Generated from an Upstream Turbine Wake," submitted to *Ocean Engineering*, 2023.