Modeling and Validation of a Cross Flow Turbine using Free Vortex Models and an improved 2D Lift Model.

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***Abstract*-A number of numerical methods have been developed to predict the performance and aerodynamic loads of the Darrieus turbine. Prior work by Reference [1] using blade element methods (BEM) and free vortex methods (FVM) [2] has produced reasonable models that predict the hydrodynamic performance of the Darrieus turbine. The validated models reasonably estimate the performance at low solidities (Nc/R<<1), but lose accuracy at higher solidity ratios. Dynamic stall and flow curvature has been recognized by [2] [3] and [4] to be significant modeling parameters which have limited the accuracy of prior models. The current numerical model extends the predictions of the FVM model to a higher solidity ratio range. An improved model is presented for the condition of high angles of attack and for dynamic stall,. Experimental data on a series of two (Nc/R≈.9) and four (Nc/R≈1.8) blade configurations are presented as validation of the modified analytical vortex model.**

Tidal Energy has the potential to be an important source to diversify and provide affordable renewable power to people near coastal areas. However, some of the best tidal currents available are near sensitive areas for fish spawning and feeding. For this reason, any device that is to be designed for installation in this environment has to minimize impact on these fragile ecosystems. The Darrieus turbine offers an attractive alternative design because of these environmental considerations. High solidity turbines are of interest since they operate at lower tip speed ratios and allow for lower pressure gradients along the blade. These characteristics have the potential to reduce environmental impact on marine fauna, as the conditions of excessive mechanical strike, cavitations, shear and large pressure gradients are minimized while maintaining reasonable power coefficient values.

In order to analyze the performance of the high solidity Darrieus turbine, the FVM model was chosen to model the turbine and wake with discrete vortex segments, which were then used to determine the induced velocities at the blade. Although the computational expense is greater than with other methods, like BEM models, FVM models can better predict the turbine performance at higher tip to flow speed ratios and higher rotor solidities. These methods also have the advantage of providing information of the wake profile and can be extended to provide information on the interaction of different devices.

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The lifting line FVM model requires the lift and drag curves to be prescribed for a given hydrofoil profile. Experimental data have shown that the dynamic stall contribution is higher than expected at low tip speed ratios for high solidity Darrieus turbines. Because of the complex nature of the problem, an empirical lift model based on theoretical foundation is used. An approximation of the known asymptotic limit values was used to account for the dynamic stall behavior.

In order to validate the empirical lift model for the FVM, a set of experiments was conducted using NACA 63018 blades at different toe angles, tip speed ratios, and free stream velocities. Results will be shown for a numerical model of high solidity Darrieus type cross flow turbines which have been experimentally validated. High solidity rotors (1 < Nc/R < 2) were tested and modeled for conditions of blade dynamic stall and other effects.

I. BACKGROUND

Although the tidal-current power industry is still in its developmental stages, tidal- energy is regarded as one of the most promising new alternative energy resources. Tidal energy can help reduce the environmental carbon footprint and help meet future energy demands. According to the principle of operation, tidal current turbines can be mainly classified as either horizontal or vertical axis turbines [5].

There have been many attempts to model the vertical axis turbine. The existing models can mainly be classified using Navier-Stokes equation methods and potential-flow methods. Reynolds averaged Navier-Stokes (RANS) methods can predict the performance of turbines with high accuracy, if the meshes are fine enough, but the computational cost is higher than that associated with using simple potential flow methods.

The potential-flow methods can be classified as blade element method, local circulation model and the vortex methods. The blade element method is used to predict the force on the blade of a turbine. The simplest hydrodynamic models of this type use streamtube theories. These models equate the rate of change in flow momentum in a streamtube

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to the forces on the rotor blades in that streamtube, using actuator disk theory. The various models represent the turbine as a single streamtube, multiple streamtubes [1], or double-multiple streamtube models (in which the upstream and downstream movement of the blade are differentiated) [6]. The most serious deficiency of the blade element method is that under conditions of large solidity and high tip to inflow speed ratios, the simple momentum considerations inherent in the model break down [2].

The vortex method, which is implemented and extended in this paper, is used to predict the power output and the wake of a turbine. Vortex methods are based upon vorticity equations and are used to perform detailed calculations of the induced velocity field. Vortex models can represent the blades as either lifting line or lifting surface and the wake of the turbine as either free or prescribed [6].

The local circulation model (LCM) is a combination of the blade element method and vortex models for a single streamtube. The LCM utilizes a momentum balance between the forces on the blades and the change in flow momentum as the blades pass through the rotor, and the vortex approach for the upstream and downstream flow differences.

Comparatively, the vortex method is more suitable for simulating a turbine as it provides information on the rotation of the turbine and the unsteady wake. Overall, the purpose of this study is to develop a cost-effective numerical method to simulate the behavior of a high solidity cross flow stand-alone turbine and to validate it with experimental data.

II. DYNAMIC STALL AND FLOW CURVATURE

Dynamic stall is a phenomenon that appears when a Vertical Axis Wind Turbine (VAWT) is operated at low tip speed ratios. It is created when unsteady loads and flow separation release large vortices that influence the forces on the blade. Dynamic stall has a significant impact on the loading on the blades and consequently on the power output of the turbine [7]. VAWTs are also subject to cyclic forces so that the ability to accurately predict the forces on the blade is critical to accounting for fatigue in the design of the turbine.

The dynamic stall behavior of a VAWT turbine is similar to blade pitching in large angles of attack. As the blade changes its angle of attack relative to the flow, dynamic stall occurs as a leading-edge vortex is shed from the blade. This produces an increase in lift, a negative pitching moment, and an increase in drag on the blade. The dynamic stall phenomenon has been reported to present limited sensitivity to many parameters [8].

Due to the fact that high solidity Darrieus turbines have relatively slow operational tip speed ratios, they operate at higher angles of attack that lead into the post stall area. Modeling the VAWT is further complicated by the fact that the blade is also influenced by the wake of previous rotations and the variation in perceived velocity during its upstream and downstream movement.

Numerous numerical and analytical methods have been developed for the direct calculation of dynamic stall on an oscillating airfoil. This is an active area of research in classical fluid mechanics. Presently, these methods remain in research or pilot stages [9].

Different methodologies to compute the dynamic stall effect have been developed for helicopter and wind turbine applications. The Gormont dynamic stall model has been implemented for VAWTs by [2] [3] [10]. Another popular model used to account for dynamic stall is the Beddoes-Leishman (B-L) model. It provides an overall representation of the unsteady phenomenon. The B-L model is commonly used for helicopter blade aerodynamic modeling for Mach Numbers above 0.3. Reference [11] has given recommendations for extending its use for lower Mach number applications.

Flow curvature is an important phenomenon in cross flow turbine blade hydrodynamic efficiency and its proper consideration can improve performance calculations, even for lower blade to radius ratio (c/R) cross flow turbines. Its effect is even more noticeable on the hydrodynamics of higher blade to radius ratio (c/R) cross flow turbines. This phenomenon is caused by unusually large boundary-layer radial pressure gradients and virtually altered camber and incidence [4].

The cost of direct numerical simulation of such a system would make the computational cost very high, if implemented in current models. Simple approximations for these phenomena must therefore be considered.

III. ANALYTICAL MODEL

In order to develop the analytical model the following assumptions were made:

- The tidal turbine works as a stand-alone turbine.
- The incoming flow is uniform.
- The lift and drag coefficients on a blade element are calculated by using semi-empirical curves.

As other requirements of the research conducted include, flow profile data, wake decay and pressure gradients before and after the turbine, a FVM model was chosen to be implemented.

IV. NUMERICAL MODEL

A modified FVM model was used. This model is based on previous work by Reference [2]. A simplified flow chart of the model is shown in Fig.1:

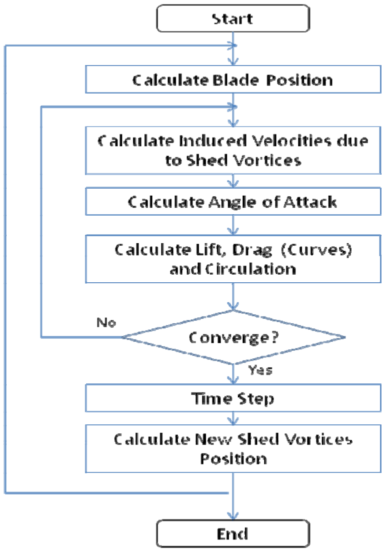


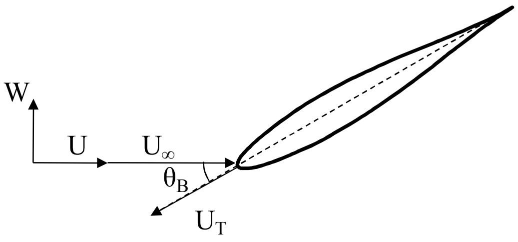
Figure1. Flowchart of a modified Free Vortex Method (FVM) model

This model requires the input of the blade position, to calculate the induced velocities due to shed vortices. The vortex considered in this model is the Rankine vortex type

$$\vec{V}_P(i,j) = \frac{\vec{h} \times \vec{\Gamma}}{2\pi h^2} \tag{1}$$

The induced velocity is the sum of the velocities induced by all shed vortices and new vortices in the computational domain.

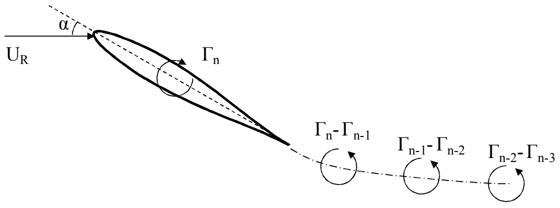
The angle of attack is calculated from the relative velocity. The following is used to calculate relative velocity



$$\vec{U}_R = (U_\infty + U + U_T \cos\theta_B)\vec{i} + (W - U_T \sin\theta_B)\vec{k} \tag{2}$$

where U_∞ is the undisturbed free stream velocity in the x direction and U and W are the induced velocities in the x and z directions, respectively. The induced velocities consider the vortices filaments that include both the blade bound and wake vortices. The tangential speed of the blade element is given by U_T.

The angle of attack can be obtained by solving the relative velocity seen by the blade.



$$\tan\alpha = \frac{(U_\infty + U)\sin\theta_B + W\cos\theta_B}{(U_\infty + U)\cos\theta_B - W\sin\theta_B + U_T} \tag{3}$$

The lift and drag generated by the incoming flow are directly related to this angle of attack. The lift and drag coefficients are interpolated from the input lift and drag coefficient table. The bound vortex strength is then calculated using Kutta-Joukowski

$$\Gamma_B = \frac{1}{2} C_l c U_R^2 \tag{4}$$

Subsequently, the positions of the new shed vortices are calculated. The shed vortex strengths can be written as:

$$\Gamma_S(i, NT-1) = \Gamma_B(i, NT-1) - \Gamma_B(i, NT) \tag{5}$$

The tangential and normal forces seen by the blade are needed to calculate the power coefficient. The tangential and normal forces can be expressed as:

$$F_t = \frac{1}{2} C_t \rho c U_R^2 \tag{6.1}$$

$$F_n = \frac{1}{2} C_n \rho c U_R^2 \tag{6.2}$$

The tangential and normal coefficients in terms of lift and drag coefficients can be written as:

$$C_t = C_l \sin(\alpha) - C_d \cos(\alpha) \tag{7.1}$$

$$C_n = C_l \cos(\alpha) + C_d \sin(\alpha) \tag{7.2}$$

The torque produced by a single blade can be written using:

$$T_e^+ = \frac{1}{2} \frac{c}{R} C_t \left(\frac{U_R}{U_\infty} \right)^2 \tag{8}$$

The sum of the non dimensional torques is the power coefficient.

In order to be able to validate the modified model, the numerical outputs were compared with Strickland's experimental data. Fig. 2 shows data for a 2 blade (chord/Radius = 0.135) cross flow turbine at a tip speed ratio of 5.

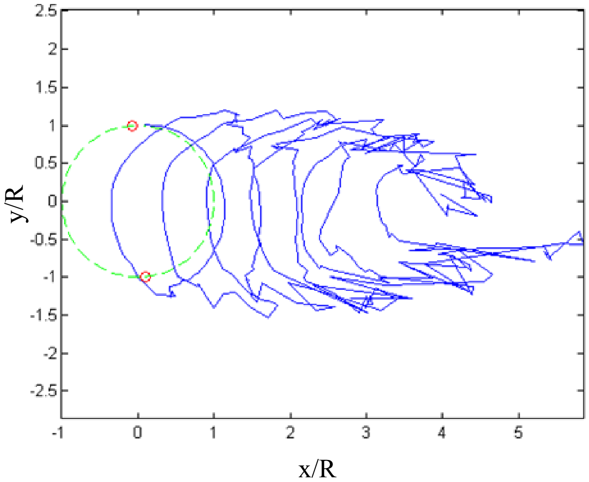


Figure 2. Analytical result of the vortex trail for the first blade

The vortex lifting line model is limited by its dependence on post stall information for the lift and drag curves, as it is not designed to model dynamic stall and cannot provide information of the pressures along the blade.

This type of the hydrodynamic models uses hydrofoil section characteristic tables (lift and drag coefficients as functions of angle of attack and Reynolds number) to determine the blade loads and turbine performance. The hydrofoil section data are usually derived from two-dimensional, static wind tunnel tests or two-dimensional, static airfoil design codes. They are then modified with empirical, semi-empirical, or analytic methods and used to estimate blade loads under three-dimensional, dynamic conditions. The greatest difficulty in obtaining accurate predictions is the determination of the appropriate hydrofoil section characteristics for the operating environment.

To represent the dynamic stall behavior at low tip speed ratios a B-L model was implemented. The ability to represent lift and drag curves with equations is an additional benefit of using the B-L model. The Kirchoff's flow equation is used to calculate the normal force for the B-L model. In order to extend the angle of attack range of this method the Kirchoff flow equation was revised considering asymptotic limits.

$$C_N = 2\pi \sin(\alpha) \left(\frac{1+\sqrt{f}}{2}\right)^2 \tag{9}$$

where α is the angle of attack and f is the separation point function.

Fig. 3 shows the approximation for a steady state curve using Kirchoff's and the modified flow equation.

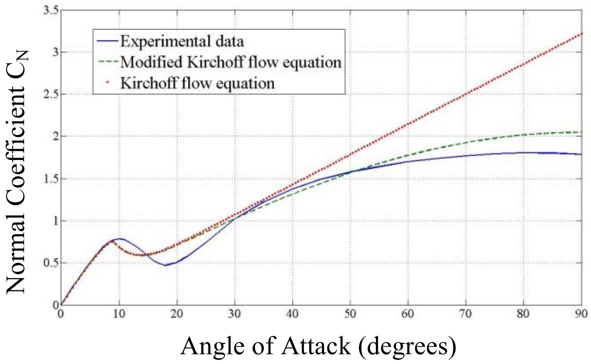


Figure 3. Normal force prediction of the modified flow equation

Considering the equation 9 and assuming that the tangential force is smaller compared to the normal force, a lift equation was derived.

$$C_L = \pi \sin(2\alpha) \left(\frac{1+\sqrt{f}}{2}\right)^2 \tag{10}$$

In Fig. 4 the results of equation 10 are compared to the basic thin plate theory and the potential flow theory which are used to approximate the lift data for an airfoil [12].

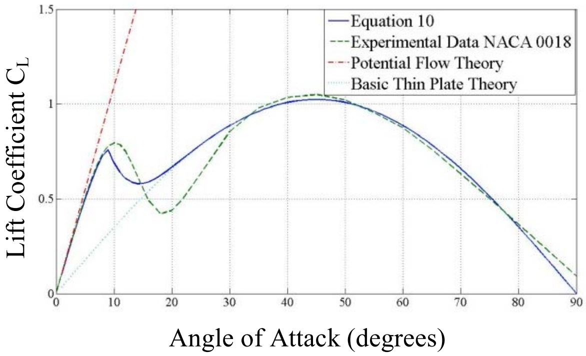


Figure 4. Lift force prediction of the analytical lift curve

The BL model used in this paper is based on the stall-onset indicators proposed by [13]. These indicators are a function of the reduced pitch rate of the blade and are used to modify the separation function values. Fig. 5 shows the response of the model to different pitch rates for a Naca 0012 profile.

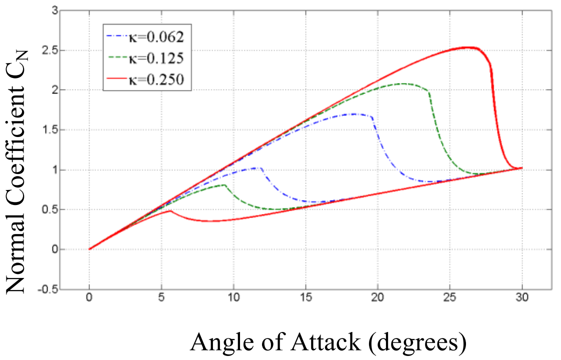


Figure 5. Modified B-L Lift curves for different reduced frequencies

The separation point function used was the piecewise exponential function proposed by Beddoes:

$$f(\alpha) = 1 - 0.4e^{\left(\frac{\alpha-\alpha_1}{S_1}\right)}, \quad \alpha \leq \alpha_1 \qquad (11.1)$$

$$f(\alpha) = 0.02 - 0.058e^{\left(\frac{\alpha_1-\alpha}{S_2}\right)}, \; \alpha > \alpha_1. \qquad (11.2)$$

The breakpoint of separation is modified by the reduced pitch rate,

$$r = \frac{\dot{\alpha}c}{2V}\,. \qquad (12)$$

For this paper the stall-onset angle of attack used was 9.68 degrees, and the values for S_1 and S_2, were 3.5 and 1, respectively.

V. EXPERIMENTAL SET UP

In order to validate the numerical investigation, a series of tidal current turbines with different blade profiles and geometries were designed, built, and tested in the towing tank at the University of Maine (UMaine). The purpose of the experimental test was to produce a more accurate simulation of a turbine in a free stream at high solidity rotor values. The turbine was tested in two and four blade configurations. Results for a four bladed turbine are presented in this paper [14].

The experimental turbine diameter was set at 0.325m. The foil section used for the blades had a NACA 63_3-018 profile with an ideal chord length of 0.0762m, of which the trailing edge was trimmed to 0.0694m to facilitate its manufacture. The length of the blades used was 0.762m. The maximum speed of the carriage during the test was 2 m/s and the turbine's tip speed ratio (λ) varied from 0.25 to 2.5.

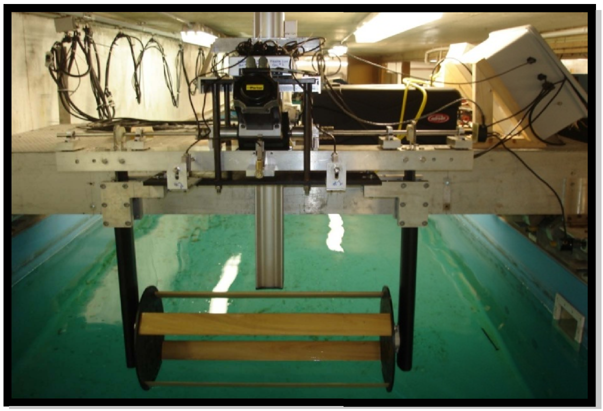


Figure 6. Cross-flow test bed developed at the University of Maine in the UMaine tow tank.

An optical encoder was used to measure rotational speed and angular position of the turbine. A load cell mounted at the motor was used to measure the torque produced by the turbine.

Figure 7. 3D Model of test bed.

Power is transferred from the turbine blades through dual chains and sprockets housed in a hydrofoil shroud to the upper test bed where the power is dissipated and measured.

The end plate is designed to be configured for three different turbine diameters, which enables the changing of the turbine solidity. Additionally, the end plate has index patterns that facilitate varying the angle of attack from +/- 10 degrees in 1 degree increments.

The power produced by the turbine is transferred to the upper assembly, Fig. 8 where a 1.75 kW servomotor coupled with a dual right angle 3:1 gear head generates or dissipates the power.

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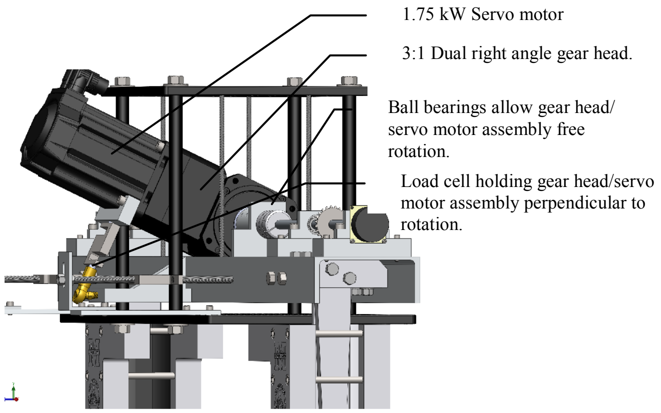

Figure 8. Upper test bed assembly.

Cross-flow turbines are unique because they are not self starting in all flow conditions. As the torque in a cross-flow turbine changes within a rotation of the turbine at different free stream velocities, a motor controller maintains the servo motor at a prescribed tip speed ratio. The motor is capable of switching between power production mode and power dissipation mode, where the electrical energy produced by the turbine is dumped to a resistor bank. The motor controller has an added benefit of enabling the acquisition of negative efficiency data to produce performance characterization at higher tip speed ratios.

VI. CROSS-FLOW EXPERIMENTAL RESULTS

For the analytical model validation, the power coefficient (as a function of λ) and the dimensionless torque (as a function of θ) were acquired and compared.

The acquired performance data was processed by bin-averaging the torque over multiple runs as a function of the turbine rotational position (θ). The analytical power coefficient was obtained using the method described in Ref [2]. In said method, the pattern of the power coefficient formed as the wake is developed after some revolutions is used to predict the final value. The non-dimensional torque for a straight four-bladed cross-flow turbine operating at different tip speed ratios with an inflow velocity of 0.762 m/s and 1.372 m/2 is shown in Fig. 9. The analytical model that does not take dynamic stall into account was shown to underpredict the power coefficient at low tip speed ratios. As was expected, the maximum power coefficient that was experimentally acquired at lower tip speed ratios than what was seen in lower solidity cross flow turbines. This difference can be attributed to the dynamic stall phenomena which produces higher normal and tangential forces when the blade pitches at relatively high angles of attack.

From the experimental data it was also apparent that the turbine's power output at different inflow speeds is relatively insensitive to changes in the Reynolds number. Dynamic stall has been reported to present this insensitivity to Reynolds number, which has been attributed to a dominating effect on the loading of the dynamic stall [8]. This result needs further study.

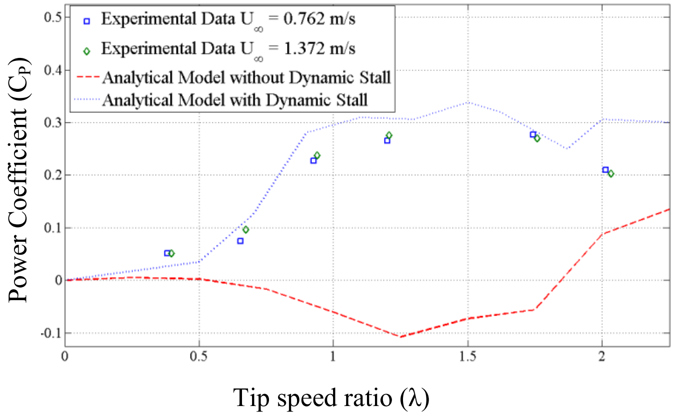

Figure 9.The overall non dimensional coefficient of performance versus tip speed ratio for 0.762 and 1.372 m/s inflow velocities.

The torque curves of the experimental data was compared against the curves of the analytical data of the model that take into account the dynamic stall and to that of the unmodified model represented in Fig.10 at a tip speed ratio of 0.5 at 1.372 m/s. The blue dotted line represents the experimental data. The proposed vortex model and the unmodified vortex model are represented by the green line and the red dashed line, respectively. At this tip speed ratio the dynamic stall phenomenon is quite apparent as the turbine was not expected to have large torque values. The steady increase in the angle of attack(as in a ramp-up test) is the result of operating the blade at low tip speed ratios.

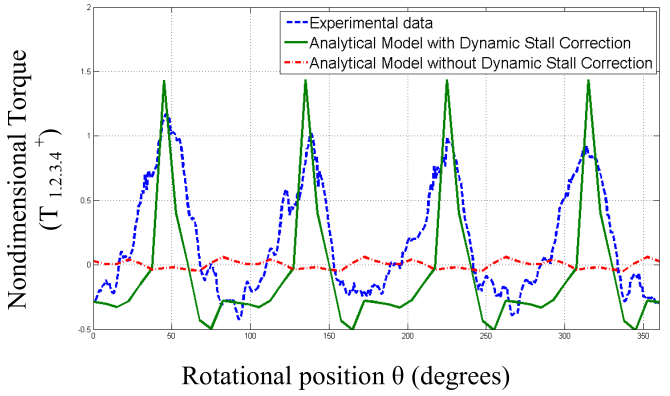

Figure 10. Unsteady state non-dimensional torque versus turbine rotational position.

VII. CONCLUSION

This paper mainly describes the implementation and validation of a vortex method model with dynamic stall correction for estimating the performance of a high solidity cross flow tidal-current turbine. The normal and tangential curves produced by the B-L model provided results that were in line with the experimental data for two and four blades obtained in the towing tank at UMaine. Additionally, the corrected numerical model for the 2D case provided better power output estimates even in cases of relatively high stall regimes.

As high solidity cross flow turbines operate at high stall regimes, it is important to correctly define dynamic stall on-set criteria. This will provide correlations to better approximate the dynamic stall phenomena.

The corrected model with its low computational cost can be an option to predict the interaction of an array of turbines with its associated wake and velocity profiles.

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