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Blade Element Momentum Theory to Predict the Effect of Wave-Current Interactions on the Performance of Tidal Stream Turbines

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***Abstract*—The durability and reliability of tidal energy systems can be compromised by the harsh environments that the tidal stream turbines need to withstand. These loadings will increase substantially if the turbines are deployed in exposed sites where high magnitude waves will affect the turbine in combination with fast tidal currents. The loadings affecting the turbines can be modelled using various numerical or analytical methods; each of them have their own advantages and disadvantages. To understand the limitations arising with the use of numerical solutions, the outcomes can be verified with practical work. In this paper, a Blade Element Momentum coupled with wave solutions is used to predict the performance of a scaled turbine in a flume and a tow tank. The analytical and experimental work is analysed for combinations of flow speeds of 0.5 and 1.0 m/s, wave heights of 0.2 and 0.4 and wave periods of 1.5 and 1.7 s. It was found that good agreement between the model and the experimental work was observed when comparing the data sets at high flow conditions. However, even if the average values were similar, the model tend to under predict the maximum and minimum values obtained in the experiments. When looking at the results of low flow velocities, the agreement between the average and time series was poorer.**

***Keywords*— Tidal Turbine, Blade Element Momentum Theory, Wave-Current Interactions, Experiments, Loading.**

I. INTRODUCTION

The development of the marine renewable energy industry is growing rapidly with new developments all around the globe. Atlantis Ltd has just signed a contract to explore the use of tidal stream energy in Japan [1] while the Swedish company, Seabased, has signed a partnership to provide renewable energy to Sri Lanka, starting with the installation of a farm to power a fish farm [2]. While those are terrific news for the marine energy industry, there are still many challenges that need to be tackled before the industry is economically viable.

One of the main contributors related to the rapid failure of the marine renewable energy converters, is the complex and variable nature of the resource. For tidal energy conversion, tidal stream turbines need to work under sever flow velocities with fluctuating turbulence intensities in the region of 10% [3]. This turbulence is also accompanied with turbulent length scales that can affect the durability and reliability of a TST. Lately, the quantification of the effects that the turbines need to withstand in exposed locations with wave-current interactions has also become of importance.

The interactions of wave and currents with TSTs have been studied numerically and experimentally by a few authors. [4] and [5] explored the use of Blade Element Momentum Theory (BEMT) and Computational Fluid Dynamic techniques (CFD), respectively, to investigate the effects of oscillatory motion of waves in TST blades and on the drivetrain. They found out that the combination of wave-current interactions has a large effect on the bending moments occurring on the turbine which will translate into damaging effects of the drivetrain components. While the work undertaken by [4] and [5] allowed the investigation of wave-current interactions with a few changes of wave and current parameters, the numerical model predictions need to be verified to understand the limitations of each of the numerical models when compared to experimental tests.

Experimental research related to wave-current interactions with TSTs have been undertaken several authors, e.g. [6] - [7]. As it can be seen there are different aspects that each of the authors have tackled in each of the testing campaigns. Initially, [6] used a 0.4 m diameter turbine to investigate the effects that different wave periods and heights at different flow speeds had on the turbine. The results presented in this work provided an initial understanding of the detrimental effects that wave-current interaction can have in TSTs by comparing out of plane bending moments occurring on the rotor using a combination of numerical and experimental work. However, the work presented there is somewhat unclear on the specific outcomes for each of the testing conditions. [8] investigated the effects of wave-current interactions on a 0.9 m diameter by varying two wave periods and two heights with a total number of three cases. It was found that the average values of torque and thrust remained similar to the cases without wave influences. But the fluctuations arising from the wave-current interactions on the loading of the rotor were in the region of two or three times of magnitude. This investigation was insightful but restricted to small size wave heights of 0.2 m and wave frequencies between 0.5 and 0.7 with low flow velocities of 0.6 m/s. [9] undertook an experimental analysis on wave current interactions with a turbine of 0.5 m of rotor diameter using a single flow speed of 0.5 m/s and two waveforms. The experiments were carried out in a flume facility and it was found that average values of power and thrust remained similar for the wave and no wave conditions. The fluctuations of power and thrust showed to be significantly high, using standard deviation values; however, it was difficult to quantify the actual peak variations of the time or frequency domain signals. [7] undertook an experimental campaign where the temporal variations of loadings were analysed on a scaled turbine of 0.5 m diameter working under larger amplitude waves. The turbine operated at 1.0 m/s. Later, the same turbine was tested at a flume facility aiming to replicate the tests done at the tow facility; however, due to the limitations of the facility, only the 0.5 m/s tests were carried out. The information from these testing campaign will be used in this investigation.

As it can be observed the tests that have been carried out up to date are usually limited by the testing facility or the turbine design; therefore, alternative methods to experimental research is the use of analytical tools. To investigate the effectiveness of either the numerical methods used at diverse conditions; i.e. flow velocity, wave conditions, etc, this paper aims to compare simulations undertaken using an in-house BEMT code able to quantify loading with combined waves and current with experimental results obtained with a turbine working at two flow speeds in two different facilities at similar wave conditions, when possible.

II. Methodology

A scaled horizontal axis turbine of 0.5 m diameter was employed in the experimental campaigns and in the BEMT model. The turbine is composed of three blades with Wortmann FX 63-137 aerofoil profile. The rotor blades used have a Wortmann FX 63-37 profile. The rotor has a radius of 0.25 m, with a hub radius of 0.05 m. The optimum pitch for this design is at 6 degrees. This pitch setting was set by adjusting the blade root to the hub with a grub screw. Further details of the blade geometry, including the chord length and twist can be found in [10].

Flow speeds of 0.5 m/s and 1.0 m/s were tested and simulated based on the experimental campaigns undertaken at two facilities (carriage speed used in the tow tank and current speed used in the flume are both referred here as flow speeds). These parameters are considered here as Case CO1 and CO2. Three additional cases were also contemplated using different combinations of wave heights and periods. Case WF1 refers to a flow speed of 0.5 m/s with a wave height of 0.4 m and an apparent wave period of 1.71s. The apparent period considered the movement of the tow carriage towards the waves generated at the end of the facility, as proposed in [11]. Therefore it simulates as if the current and the waves travel in the same direction. WF2 attempted to replicate the same wave conditions in a flume tank. Due to the limitations of the facility, a wave height of nearly 0.2 m and a period of 1.71s was used in the experiments. Case WF3 related the wave-current experiments that were undertaken at Insean at 1.0 m/s. The wave height for this current speed was set to 0.4 m and an apparent wave period of 1.5 s.

The cases simulated using BEMT and explored in the testing campaigns are summarised in Table 1.

Table 1 Testing programme

Cases	Flow Speed (m/s)	Wave height (m)	Wave Period or apparent wave period (s)	Type of facility
CO1	0.5	-	-	Flume and Tow
CO2	1.0	-	-	Tow
WF1	0.5	0.2	1.7	Tow
WF2	0.5	0.2	1.7	Flume
WF3	1.0	0.4	1.5	Tow

A. Blade Element Momentum Theory

Blade Element Momentum Theory (BEMT) is widely used in the renewable energy sector. It has been used extensively to model the performance of wind energy turbines and now its use has been extended to the marine energy industry. The theory is based on the conservation of axial and angular momentum where power and thrust can be inferred. The annular section representing the turbine rotor is then split into a number of elements in the radial direction. Thus, each of the elements is analysed independently to calculate normal and tangential forces using aerodynamic coefficients as complementary information to solve the set of equations. This means that depending on the blade geometry and the inflow characteristics, the lift (Cl) and drag (Cd) coefficients which are related to the forces acting on the blade sections will change. Therefore, when estimating power and thrust using BEMT, the Cl and Cd parameters utilised can have a high influence in the outcomes.

Cl and Cd coefficients can be obtained from several sources. A database of a large number of aerofoil coordinates and their performance at diverse Reynolds numbers can be found in [12]. If the required parameters are not covered by the available literature, the coefficients can be calculated using numerical models, e.g, Xfoil, Profil 07, Javafoil. For this investigation two different Reynolds numbers were used for the calculation of power and thrust coefficients for a Wortmann FX 63-137 aerofoil.

The BEMT model used in this investigation was developed at Strathclyde University [4]. Prandtl tip and hub loss correction factors were utilised in the BEMT calculations. Buhl correction was implemented to account for axial induction factors higher than the theoretical upper limits and the Viterna-Corrigan method was applied to estimate high flow angles during post stall values. A similar approach was undertaken in [13]. The influence of waves was taken into account by using the Morison equation which considers the drag and inertial forces on a submerged body in oscillatory flows.

B. Experimental Campaigns

For the experimental campaign, a 0.5 m diameter turbine was used to validate the numerical model described in the previous section. The diameter of the turbine is slightly smaller in size compared to other devices in the range of 0.7 to 1 m in diameter. However, it was observed by [14] that it was possible to achieve Reynolds independency at flow velocities larger than 0.9 m/s.

Experiments were undertaken at two facilities, a tow tank located in the CNR-INSEAN laboratory in Rome, Italy and a circulating flume tank based on the Ifremer research centre at Boulogne Sur Mer, France. Figures 1 and 2 show the prototype installed at each facility. The horizontal axis turbine used in both experiments was designed at Cardiff University. Within this section, the test program, the experimental setup, and the blade and turbine geometry are described.

Table 2 Details of the tow and flume tanks

Facilities	CNR-INSEAN	IFREMER Centre
Facility dimensions	220 m × 9 m × 3.5 m	18 m × 4 m × 2 m
Flow velocities tested	0.5 m/s	0.5 and 1.0 m/s
Turbulence intensity	0%	1.46%
Blockage ratio	0.62%	2.4%

B.1 Experimental setup, turbine design and instrumentation

The turbine was secured using a vertical stanchion in both facilities 1.0 m below the free surface of the water. The stanchion was made of steel. In the tow tank, the stanchion was installed to the towing carriage using a couple of brackets mounted to the carriage structure, as it can be observed in Figure 1. In the flume tank, the turbine was installed from the top part of the tank using four triangular frames attached to two I-beams that were placed across the flume on the top. Similarly to the installation used in the tow tank at CNR-INSEAN. Two bracket were placed along the vertical stanchion, as observed in Figure 2.

The main advantage of the small rotor size used is that it is possible to achieve blockage ratios sufficiently small so it is not required to apply any correction factors. As it is observed in Table 2 the blockage ratio achieved in the tow tank facility at CNR-INSEAN was of 0.62% whereas a slightly major percentage was quantified at Ifremer, but still at the low proportion of 2.4%.

Speed control to set the required tip speed ratio was used for the entire test programme. This was established by controlling the Rexroth IndraDyn Synchronous-Torquemotors motor which was installed at the back of the turbine. The turbine did not include a torque meter within its casing; however, torque was captured using the torque generating current (TGC) logged from the motor. The TGC is basically the required current to maintain the turbine rotating at a certain speed or torque. As this current comes from the motor itself, a pre-calibration is required to remove the friction related to the system. This pre-calibration is undertaken by removing the blades and rotating the rotor at different velocities. This frictional losses are then subtracted from the logged TGC to obtain the final outcome. More details on the motor calibration can be found in [7].

For the tests carried out at the CNR-INSEAN, a custom built quarter bridge strain gauging system was incorporated in the one of the blades to measure the load at the root. During the tests carried out at Ifremer, a full bridge configuration on the stanchion was includes at 1.5 m from the mid-hub height (0.5 m above the free surface). This distance was calculated to void interference from the brackets used to install the turbine. Both gauges systems were calibrated in dry environments by applying a variety of weights to obtain an output voltage which related the loads and the analogue outputs. A pre-calibration was also undertaken during the testing campaign, where data was gathered during steady conditions; i.e. flow speed was zero, to verify any trace of drifting in the signals.

Figure 1. Turbine installed at the tow tank at CNR-INSEAN

Figure 2. Turbine installed at the flume facility at Ifremer.

For the tow tank tests, the flow velocity and the wave height and period was monitored during each of the tests using a pitot tube and a wave probe installed next to the turbine at the same height as the rotor hub (1.0 m as mentioned previously). For the flume experiments at Ifremer, a laser Doppler velocimeter was installed 7.2 diameters (D) upstream the rotor at 1.0 m below the free surface. Three resistance wave probes were installed next to the turbine to measure the wave heights during the operation of the turbine. More information of both testing campaigns can be found in [7] and [15]

For both testing campaigns, National Instruments LabVIEW was used as the data acquisition system.

C. Data Processing

For comparative purposes, the rotor torque, thrust, and rotational speeds were averaged over time for each test. Non-dimensional values of power and thrust for the experimental and BEMT will be used. These are based on the following formulas:

$$C_P = P/0.5\rho A V^3$$
$$C_T = T/0.5\rho A V^2$$

where P is average power in Watts, and T is the average thrust in Newton (N). A is the swept area of the rotor in meters, and V denotes the unidirectional flow velocity (m/s), in these tests this is the average flow measured at the hub height in the flume and the carriage velocity when looking at the tow tank tests.

The average C_P and C_T are plotted against the average TSR values for each test run. TSR denotes the ratio between the blade tip speed and the flow velocity (V):

$$TSR = \Omega r/V$$

where Ω rotor speed in rad/s and r is the radius of the turbine.

III. Results and Discussion

This section presents the comparative results obtained with BEMT and the experimental campaigns. The first section includes average values of power and thrust shown in its non-dimensional form using equations 1-3. The second section, shows selected cases where the time series of torque and thrust are compared between the analytical and experimental values.

A. Power and Thrust Coefficients

Figure 3 includes the "current only" cases, i.e. no waves are included in the analytical model or in the experimental campaigns, at flow speeds of 0.5 m/s. It can be noticed that the results obtained at the turbulent flume (ifremer) are slightly higher than those obtained at the towing tank (Insean). Since this discrepancy is only of about 10% between the experimental campaigns it is possible that this might be related to the uncertainty of the experiment and the turbulence seen at the flume. When looking at the BEMT predictions, it is noticeable that the disparity between model and experimental data is in the order of 30% where the analytical model is over-predicting the values of torque generated by the turbine.

Figure 4 includes the experimental and analytical cases when the turbine operated under the influence of waves and a flow speed or carriage speed of 0.5 m/s. Similar to the current only conditions, the C_P values are in the same order when compared to the experimental cases; however, contrary to what was observed previously, the average values of power are slightly higher in the tow tank than in the flume. This might be related to the shear flows obtained at a flume facility. In this paper, only the average flow speed at the hub centre was used to calculate C_P; therefore, the influence of a shear profile is not captured in the experimental results. This however is not a major concern given the fact that the analytical model is also set to compute torque and thrust values with a set flow speed of 0.5 m/s (and later on at 1.0 m/s).

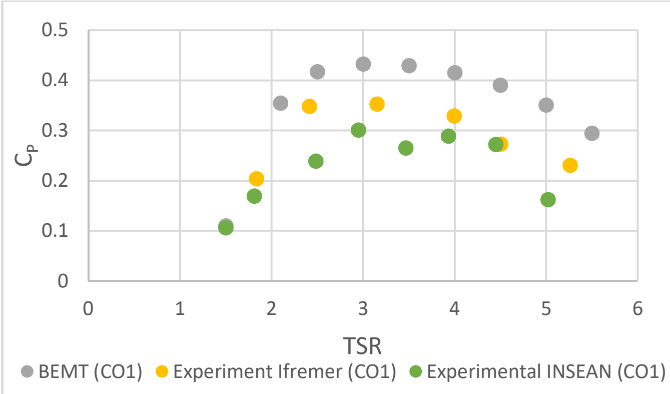

Figure 3. C_P comparison between BEMT and experiments undertaken at two facilities for the 0.5 m/s case when the turbine operates under current only conditions.

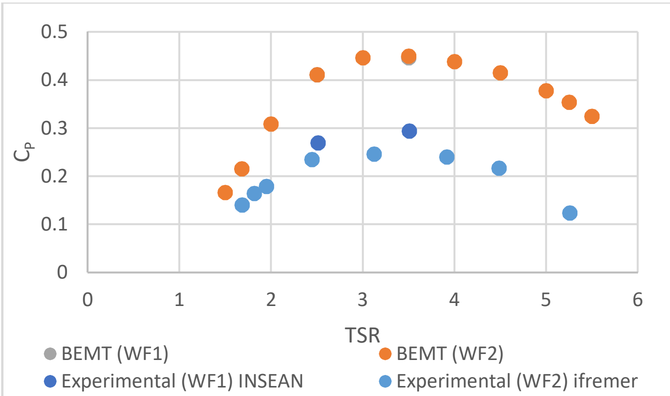

Figure 4. C_P comparison between BEMT and experiments undertaken at two facilities for the 0.5 m/s case when the turbine operates under wave-current interactions with a wave height of approximately 0.2m and a wave period (or apparent wave period) of 1.7s.

Figures 5 and 6 show the comparison of the average C_T values obtained for the experiment and BEMT. As mentioned earlier, thrust measurements of the rotor were only acquired during the testing campaign undertaken at Ifremer and thus, only for flow velocities of 0.5 m/s. For the *current only* condition, the match between the experimental values and BEMT follows the same trend for most of the C_T-TSR curve (Figure 5). With TSR values $\geq$ 4 the discrepancy between BEMT and experiment increases, where the experimental values tend to increase in value with TSR and the analytical model predicts an opposite trend.

In Figure 6, a large disagreement between the experiment and the analytical model can be observed. For all the TSR cases, the analytical values are about 18% higher than the experimental data. This can somewhat be expected as the power predictions were also higher (by approximately 40% in the wave cases) when power was quantified using the BEMT model.

There are a couple of reasons that may explain the differences between the thrust values of the experiment and the BEMT model. As mentioned in Section II-B, thrust was measured in the experiment by incorporating a full bridge of strain gauges in the stanchion used to support the turbine in the flume. Therefore, instead of measuring actual thrust, the real data acquired was a bending moment rather than the actual thrust developed by the turbine. This can be corrected by acquiring information of the setting used in the experiment under the pure influence of the flow variations, i.e. current only and wave and current conditions when the turbine is not operating. Moreover, the calibration of the stanchion should be done using the exact setting of the experiment, i.e. the calibration should be done in site. Another option is to "dry" calibrate the stanchion using a similar setting as the one used in the laboratory, in this case, by mounting vertically the stanchion and applying a variety of loadings in the horizontal direction, to simulate the loads created by the turbine. Due to laboratory and time constrains, the calibration of the stanchion in these experiments was done horizontally and the loading was applied vertically, which may give an insight of the voltage vs loading trend; however, the outcomes may translate in a large experiment uncertainty.

Another factor that may influence the thrust measurement on the stanchion is related to the shear flows observed in the flumes. It has been observed in [16] that the variability of the flows in that facility is highly affected by the use of the wavemakers on the flume facility.

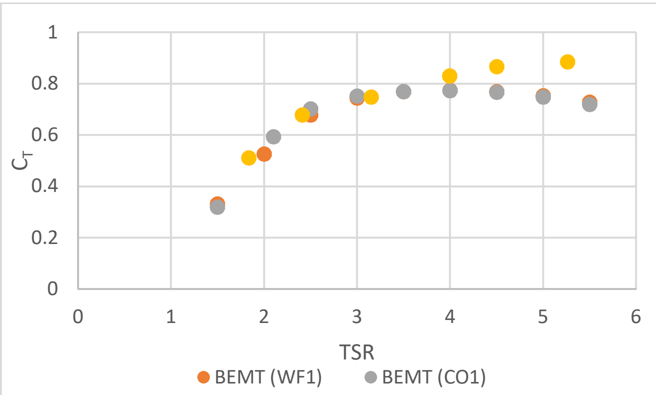

Figure 5. C_T comparison between BEMT and experiment for the 0.5 m/s case when the turbine operates under current only conditions.

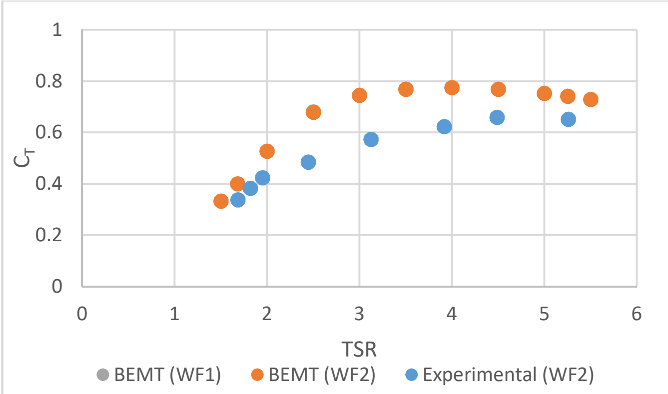

Figure 6. C_T comparison between BEMT and experiments undertaken at Ifremer for the 0.5 m/s case when the turbine operated under wave-current interactions with a wave height of approximately 0.2m and a wave period of 1.7s.

Figures 7-9 show the comparisons of C_P and C_T for the 1.0 m/s cases. It can be observed a good agreement on the power coefficient between BEMT and the experimental for both current only and wave cases and for most of the TSR values. The major discrepancy observed in the average values of C_P for the experiment and the BEMT was approximately 7% for a TSR = 2.3; however, the other cases presented disparities of about 2%.

For the C_T comparisons, limited data was available from the testing campaigns to corroborate the simulations undertaken in BEMT. This is one aspect that will be further investigated in the future. However, for comparisons purposes, both average values of C_T for simulations done with and without waves are presented in Figure 9. It can be observed that the models predict similar average values for both cases as it was to be expected, especially since at this point shear flows are not considered in the calculations.

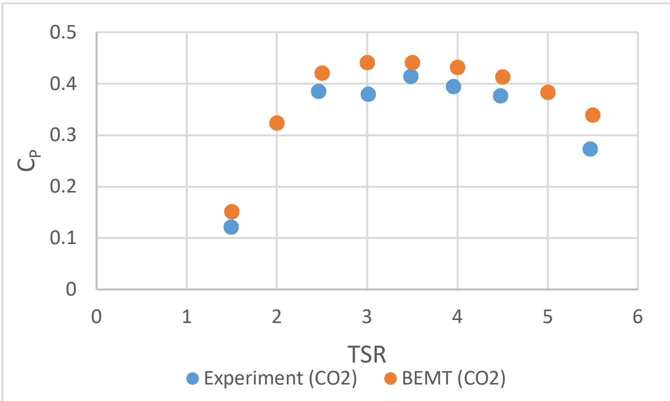

Figure 7. C_P comparison between BEMT and experiments undertaken at Insean for the 1.0 m/s case when the turbine operates under current only conditions.

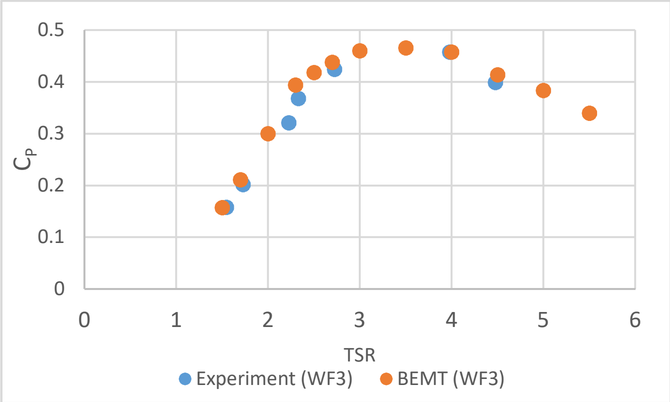

Figure 8. C_P comparison between BEMT and experiments undertaken at Insean for the 1.0 m/s case when the turbine operated under wave-current interactions with a wave height of approximately 0.4m and an apparent wave period of 1.5s

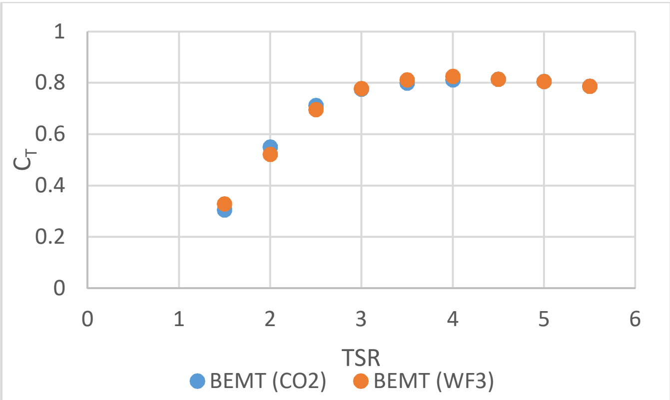

Figure 9. C_T comparison between BEMT calculations for the 1.0 m/s case during "current only" conditions and when the turbine operated under wave-current interactions with a wave height of approximately 0.4m and an apparent wave period of 1.5s

B. Torque and Thrust Time Series

In this section the time series obtained with the model and the experiments are compared for selected cases of torque and thrust. For the 0.5 m/s cases, TSRs of 1.7 and 5.25 were selected since it was observed in Figures 3-6 that these cases presented a better agreement between model and experiment. The experimental data used here was that obtained from the flume campaigns as both torque and thrust signals were recorded during those trials.

It can be observed in Figures 10 and 11, that the fluctuations of the time series obtained with BEMT are in the order of 0.01 Nm and 0.28 N for the torque and thrust simulations, respectively, whereas these fluctuations increased to 0.33 Nm and 7.35 N when looking at the experimental information. It is noticeable in Figure 10 that the turbine did not generate any torque in a few instances of the test run; i.e. the turbine was driven by the motor. Evidence gathered from the calibration procedures [7], showed that there is a larger scatter in the calibration of the motor when capturing TGC which may have influenced the torque information, especially since the turbine was not generating any power at such low flow speeds. For the thrust, one of the reasons related to the discrepancy between experiment and model may be related to the fact that the stanchion was working not only under an axial force developed by the turbine but also the shear flows generated at the facility. As mentioned previously, the shear flows are not captured using tBEMT model as in this simulations a set flow is used in the inputs of the simulation run.

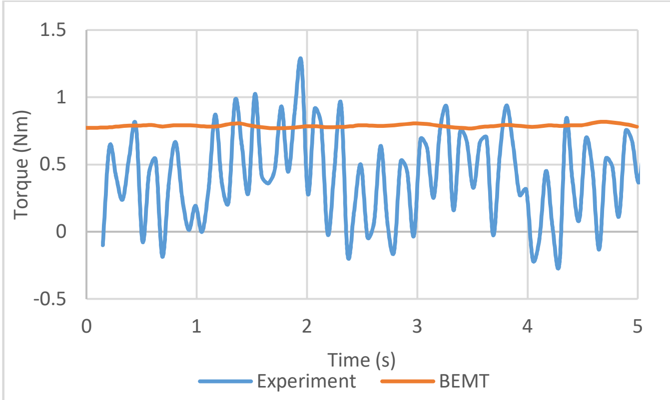

Figure 10. Comparison of BEMT and experimental variations of torque for a wave height of 0.2m. wave period of 1.7s and TSR =1.7

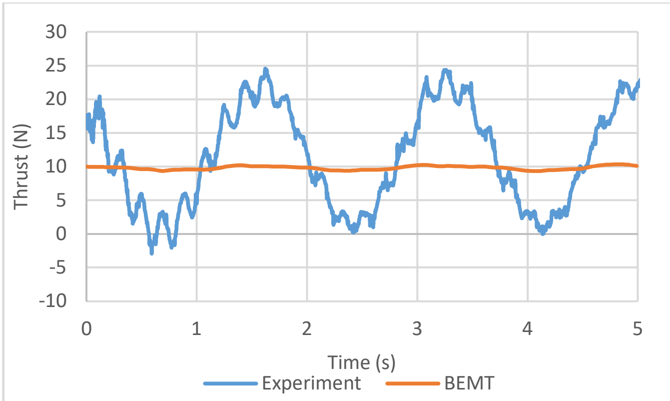

Figure 11. Comparison of BEMT and experimental variations of thrust for a wave height of 0.2, wave period of 1.7s and TSR =1.7

The match between BEMT and experiment is slightly better for the case of TSR=5.25. The amplitude of the signals both for the model and for the experiment follow a clear sinusoidal pattern, as expected, due to the wave-current interactions. The variability of the signals is 0.26 Nm and 7.5 N obtained in BEMT and 2.9 Nm and 12.6 obtained for the experiments done at the flume. It is clear that the fluctuations predicted by BEMT are smaller than those obtained in the experiment.

The difference of the peak torque and thrust were also quantified using both the BEMT model and the experimental data; i.e. the difference between the maximum and minimum. A torque amplitude of 0.73 N was obtained using BEMT while the amplitude quantified from the experimental signals was 40% higher. Similarly, the thrust amplitude was 38% higher for the experiment than from the BEMT prediction.

Figures 14-16 shows the comparative results between the model and the experiments for flow (or tow in this case) speeds of 1.0 m/s. The figures were obtained using a wave period of

1.5 s and a wave height of 0.4 m and TSRs of 2.75, 4.0 and 4.5. It can be observed that there is a good agreement between the model and the measured torque for all the cases. Even though the mean values showed in Figure 8 are close between the experiment and BEMT, it is noticeable that the torque variations predicted by BEMT are lower in magnitude compared to that measured in the testing campaign. For the three TSR cases selected here, it was calculated that the amplitude of the torque signals was approximately 40% higher in the experiments than those predicted by BEMT.

This highlights the importance of verifying numerical models when designing a full scale tidal stream turbine. It is knows that most of the predictions of torque and thrust are used to engineer most of the components used in a turbine. Using lower predictions of loading fluctuations when designing a device may translate into a rapid failure in the turbine components.

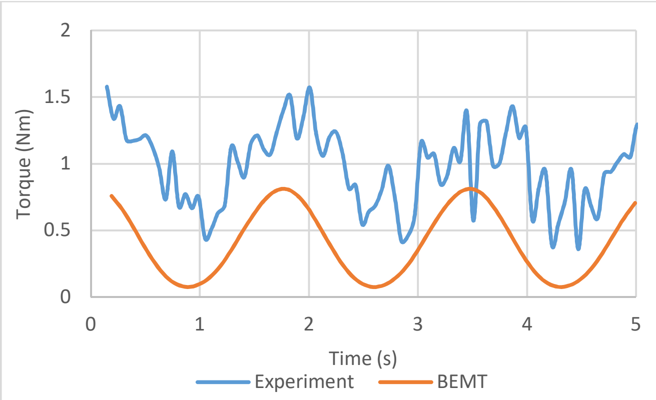

Figure 12. Comparison of BEMT and experimental variations of torque for a wave height of 0.2m, wave period of 1.7s and TSR =5.25

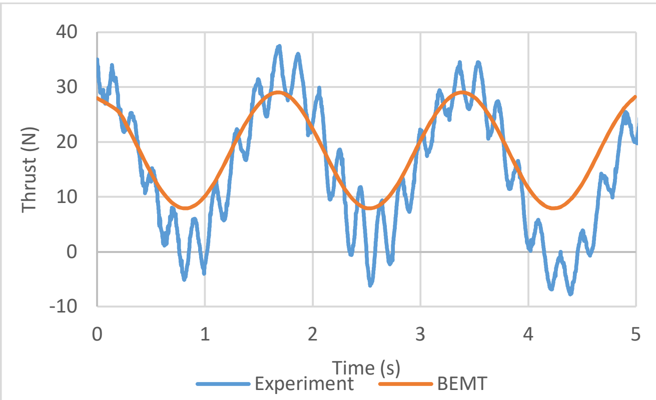

Figure 13. Comparison of BEMT and Experimental variations of thrust for a wave height of 0.2m. wave period of 1.7s and TSR =5.25

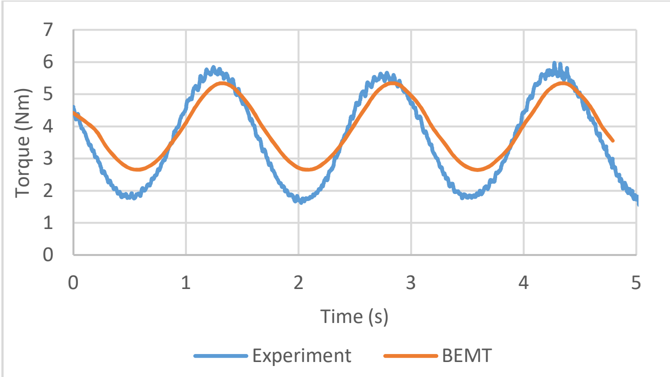

Figure 14. Comparison of BEMT and Experimental variations of torque for a wave height of 0.4m. apparent period of 1.51s and TSR =2.75

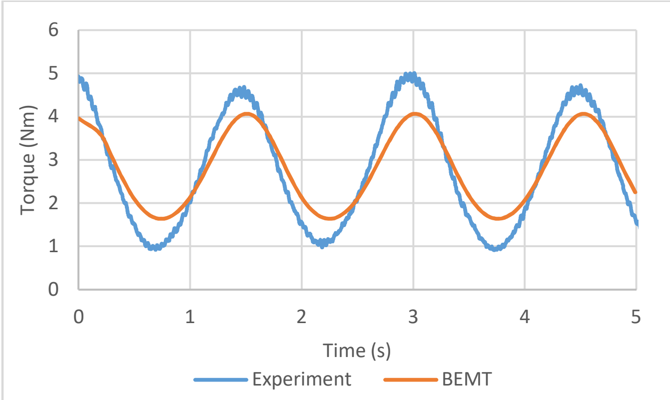

Figure 15. Comparison of BEMT and Experimental variations of torque for a wave height of 0.4m. apparent period of 1.51s and TSR =4.

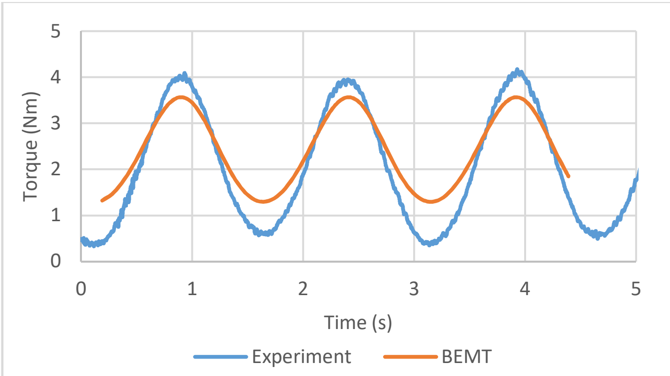

Figure 16. Comparison of BEMT and Experimental variations of torque for a wave height of 0.4m. apparent period of 1.51s and TSR =4.5

IV. CONCLUSIONS AND FUTURE WORK

Comparisons between BEMT and a variety of experimental testing campaigns were undertaken in this paper. Two flow conditions of 0.5 and 1.0 m/s were used in combinations with two wave heights. It was found that poor agreement was achieved for both power and thrust mean predictions when looking at the 0.5 m/s cases. One reason might be that the turbine was not able to generate enough power at such low flow velocities and thus the model was not able to predict those conditions. The same may be applicable to thrust; however, another reason may be related to the instrumentation used to quantify the axial loading developed by the turbine. Future work will contemplate the use of additional instrumentation when undertaking experimental work related to wave-current interactions to verify the BEMT model.

Good agreement was obtained between the model and the experimental data obtained for the 1.0 m/s cases. An approximate discrepancy observed in the average values of C_P for the experiment and the BEMT was of approximately 3%. However, it was clear that the amplitude of the torque signals obtained using the BEMT model under predict the experimental data by about 40%. Future work contemplating other wave parameters and a different rotor type will be studied in the future to understand the limitations of using the BEMT model presented here.

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