Quasi unsteady blade element momentum theory for tidal stream turbines

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Summary: As tidal stream turbines (TSTs) enter the stage of full scale prototype testing, the understanding of the loads from surface waves and currents of these devices is critical to ensure high durability and confidence in designs [1]. Presented is a preliminary method of determining the hydrodynamic loads on TST blades operating in waves and shear current profile using blade element momentum theory (BEMT). The goal of the project is to use time-series load data obtained from BEMT and conduct a fatigue analysis using FEM software. Shown in this report is a case study of a TST operating in a rough sea state.

Introduction

Due to the inherent difficulties in conducting combined wave and shear current tests on TSTs, few methodologies are available for the prediction of dynamic loads caused by combined wave and current interactions [2]. A common practice in marine engineering is to linearly superimpose the water particle velocities caused by the waves and currents in order to calculate structural loads. This is however thought to be inappropriate due to the rotational flow of a non- linear current profile used in combination with wave models based on potential theory [3]. Studies conducted by Wang (1997) [4] indicate that the coupled wave and current interactions give as much as 30% higher maximum loads on submerged structures as the individual superimposed wave and current loads. This suggests that it would be appropriate to incorporate a more sophisticated wave- current model into the methods of load prediction in order to accurately represent the TST's real operating conditions. The methodology chosen by the author to determine the cyclic and peak loads on TSTs in the combined wave- current environment, is to use a BEMT scheme in combination with a 3rd order Stokes' wave theory coupled with a linear shear current. Since the BEMT method was originally developed for steady state operation, several modifications must be made to it in order to accommodate for the dynamic inflow caused by the surface waves and tidal velocity profiles. A summary of the method is given in the next section.

Modified BEMT scheme

The main principle of the BEMT method is to equate the thrust and torque forces exerted on the fluid to the ones exerted on the TST blades along a annular stream tube. The annular thrust, $\mathrm{d}F_\mathrm{a}$, and torque, $\mathrm{d}T_1$, on the fluid are expressed as

$$\mathrm{d}F_{\mathrm{a}1} = 2\pi r \frac{1}{2}\rho U^2 4a(1-a)\mathrm{d}r. \quad (1)$$

$$\mathrm{d}T_1 = 4b(1-a)\frac{1}{2}\rho U \Omega r^2 2\pi r \mathrm{d}r. \quad (2)$$

$$\mathrm{d}F_{\mathrm{a}2} = N\frac{1}{2}\rho V^2 c(C_\mathrm{L}\cos\phi + C_\mathrm{D}\sin\phi)\mathrm{d}r \quad (3)$$

$$\mathrm{d}T_2 = N\frac{1}{2}\rho V^2 cr(C_\mathrm{L}\sin\phi - C_\mathrm{D}\cos\phi)\mathrm{d}r \quad (4)$$

where a and b are the axial and tangential induction factors, Ω is the angular velocity of the rotor, r is the radial distance of the annular section, U is the free stream velocity, N is the number of blades, V is the resultant flow, c is the blade section chord length, ϕ is the angle of the resultant flow and $\mathrm{d}r$ is the annular section thickness. The equations are set equal and solved through iteration of a and b and the elemental forces are added up. Details of the derivation of these equations can be found in [5]. To account for the spatial velocity variations across the rotor plane, each annular stream tube is divided into azimuthal sections of spacing $\Omega\,\mathrm{d}t$ where each local flow velocity is calculated as by Kishida (1988) [6]. Equations 1 – 4 are then solved for each stream tube- section individually. As the time stepping progresses, the blades are rotated to the next stream tube section and the local velocities are re-calculated, thus accounting for the time variation of the flow.

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Case study

A case study is presented where a TST is modelled in a moderate gale sea state to demonstrate the impact of wave and current loads. The parameters for the case are wave of height $H = 4$m following the flow, wave period $T = 7$s, turbine diameter $D = 10$m, current at sea bed $U_b = 1$m/s, current at surface $U_s = 2$m/s, depth $h = 30$m, hub height $h_{hub} = 15$meter, TSR = 5. At these conditions the mean power and thrust coefficients are $C_p = 0.38$ and $C_t = 0.63$. The scenario presented is illustrated in figure 1 and the blade loads are given in figure 2.

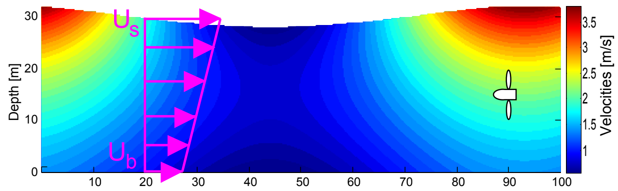
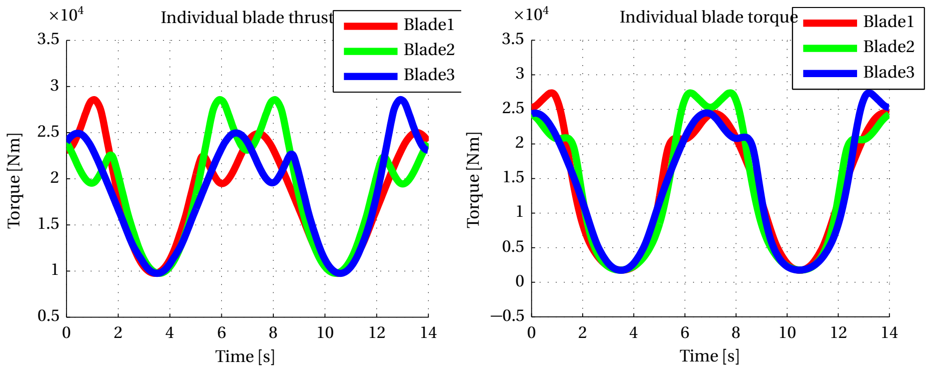


Figure 1: TST situated in rough weather site with shear current profile.



(a) Blade thrust forces

(b) Blade torque forces

Conclusions

It can be seen that the individual blade loads vary significantly during extreme sea conditions, fluctuating with as much as 2×10^4N, and that the loads across the blades also vary significantly in the radial direction (not pictured). This shows that there is a need for detailed fatigue analysis of TSTs in order to maximise their lifespan.

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