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RANS-VOF Modelling of Floating Tidal Stream Systems

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Summary: A fully nonlinear coupled CFD approach has been developed to simulate the behaviour and power output of a floating tidal stream concept. The model includes RANS-VOF and rigid body solvers based on OpenFOAM®, a hybrid-catenary mooring system and a two-way-coupled, actuator-line model for a Schottel Instream Turbine with over-speed control. Simulations are performed in spring currents at the PTEC site with and without the 1-in-1 year wave present. Results show considerable complexities beyond periodic behaviour necessitating the use of models that include the complete coupled system and hydrodynamic conditions.

Introduction

Numerical models are now capable of providing the quantitative description required for engineering analysis. However, for structures such as floating tidal stream concepts, the complete system can rarely be included using existing functionality. To better understand the behaviour of these systems, a coupled CFD model, including a floating barge, hybrid-catenary mooring system and the influence of a submerged turbine, has been developed and tested at full-scale in waves and currents based on those at the Perpetuus Tidal Energy Centre (PTEC) site.

Method

The open-source software OpenFOAM® solves the fully nonlinear, incompressible, Reynolds-Averaged Navier-Stokes (RANS) equations for air and water using the finite volume method and a Volume of Fluid (VOF) treatment of the interface. The device motion is found using a rigid-body solver and new two-way coupled actuator-line model for the turbine. Wave and current, generation and absorption are achieved via the expression-based boundary conditions and 'relaxation zone' formulation of additional toolbox waves2Foam [1].

The 18x7x1.5m buoyant barge is based on existing plans with a 'moon-pool' to accommodate a 4m diameter turbine. The computational domain is 320x60x90m with a background mesh of cubic cells (side-length 1.67m) and local multi-level octree refinement at the free-surface, on the barge surface and around the turbine.

The Schottel Instream Turbine (SIT) is a lightweight, horizontal axis turbine rated at 62kW electrical power for flows ~3ms^{-1} with a cut-in speed of 1ms^{-1}. At rated power, an over-speed control strategy including blade flexure is used. To model all of these features, an axial induction factor, a, is assumed where

$$a = 1 - U_\infty / U_T \tag{1}$$

and the thrust on the turbine is

$$T = 2\rho A U_\infty^2 a(1-a) \tag{2}$$

where ρ is the water density, A is the turbine swept area and U_∞ and U_T are the far field and local flow velocity respectively. This leads to three operating regimes with a constant a at low speeds and an a that depends on U_∞ in the two over-speed regimes (max torque, max power). A series of polynomials have been fitted to existing turbine data to predict a, as well as the angular velocity of the turbine, from U_T in these over-speed conditions.

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During the simulations, the local velocity, U_T, is approximated as the ratio of the vector sum of the weighted velocities to the sum of the weights within a cylindrical region containing the turbine. To represent the turbine blades the weights are derived using Gaussian distributions running both axially and with angular distance from each of the blade centres (which rotate at run-time according to the calculated angular velocity).

The total thrust force is then applied as an additional force in the 6DoF rigid body solver for the barge's motion. The influence of the submerged SIT on the fluid flow has been included by applying an equal and opposite distributed body force field to the momentum equation with the same weighting as for U_T.

The mooring system consists of four 235m cables (85m synthetic line, 150m chain). The full nonlinear reaction force from each cable is found using tri-linear interpolation across a 'look-up table' derived manually using OrcaFlex®. These are then applied as four further additional forces in the 6DoF rigid body solver.

Spring peak surface flow rates at the ~57m deep PTEC site are ~2.5-2.9ms^{-1} [2]. The velocity profile has been approximated using the von Karman-Prandtl equation ($U^* = 0.13$, $Z_0 = -2.24$) [3]. The waves are based on a Weibull fit to the wave data from the south-west with a return period of 1 year ($H = 6.1$m, $T = 9$s) [1].

Results

Simulations were run in spring current conditions with and without the 1-in-1 year waves. The combined case has a return period of ~85 years making it typical of the design limit state of offshore structures. Fig. 1 shows the local flow velocity, U_T (a), the thrust (b), the electrical power generated (c) and the revolutions per second (d) during simulations including currents separately (red) and waves and currents combined (blue).

It can be seen that there is significant variation in power and thrust even in the current-only case. This is believed to be due to a combination of residual surge motion and the effect of rotating blades. Unsurprisingly, the variations in the combined case are considerably more dramatic. The turbine experiences oscillations between periods of power saturation and high thrust, when a crest passes and periods of reduced power output and low thrust, when a trough passes. The revolutions per second also show correspondingly large variations.

Conclusions

The power delivery and forces on a floating tidal stream turbine show considerable complexities beyond simple periodic behaviour. Complete, coupled models, such as the one proposed here, are therefore necessary to understand the behaviour and power delivery of floating tidal stream concepts in real offshore conditions.

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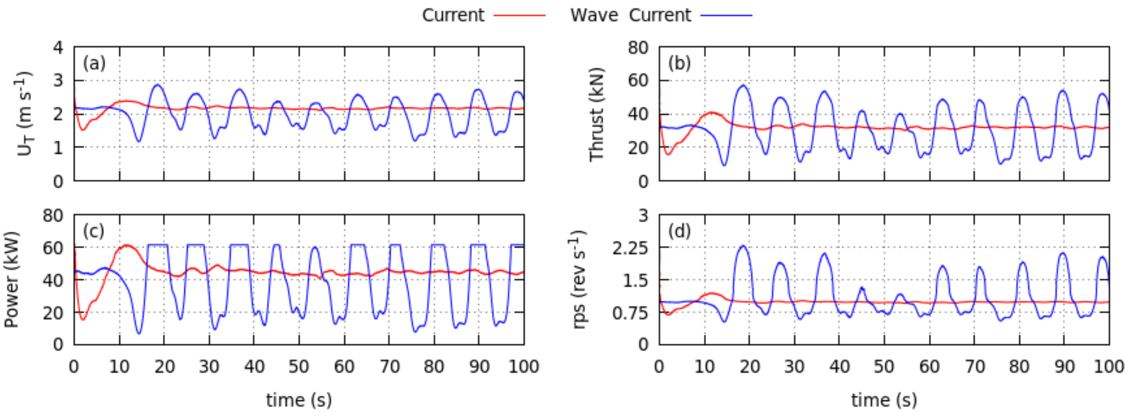

Fig. 1 Local flow velocity (a), thrust (b), electrical power (c) and the revolutions per second (d) from simulations including currents separately (red) and waves and currents combined (blue).