Effects of Dynamic Inflow and Distortion of Incident Turbulence on Tidal Turbine Rotors.

Duncan M. McNae, J. Michael R. Graham
Department of Aeronautics, Imperial College London, UK

Summary: This paper describes numerical simulation using a vortex panel free wake model and water flume experiments to evaluate added mass and dynamic inflow for unsteady flow through a horizontal axis tidal stream rotor. The reason for the much smaller inflow effect caused by changes in incident axial flow in comparison with matched amplitude and frequency changes in blade pitch is discussed. The second part of the paper analyses turbulence in the incident flow by the rotor mean flow field as it approaches the rotor plane.

Numerical simulation of unsteady flow.

The flow through a twin bladed horizontal axis tidal stream turbine has been computed using a numerical potential flow method in which the blade camber surfaces are replaced by doublet panels (or equivalently a vortex lattice) with the Kutta-Joukowski condition satisfied at the trailing edge. Vorticity is shed into the rotor wake in the form of line vortex elements which are convected as a free wake by the local velocity field. This allows the vortex wake to roll up and become displaced from the uniform helical geometry of a 'frozen' wake, as is shown in figure 1. Forces on the rotor blades are computed using the unsteady Bernoulli equation for pressures following a modified form of the method described in [1]. This is found to give the most accurate treatment of the in-plane force associated with the pressures around the leading edge of a thin blade which are singular in this lifting-surface approximation. The numerical method was used to compute the out-of-plane blade root bending moment in unsteady flow and the axial force on the rotor.

Measurements on a model rotor in unsteady flow.

Experimental measurements were also carried out on an instrumented model rotor in a water flume of width 0.6m with the rotor located at mid-depth in a water flow 0.7m deep. The model rotor was 0.4m in diameter (and hence operating under high blockage conditions) with two blades of NACA6412 section. It rotated about a horizontal axis, mounted on a single thin, vertical support strut of approximately 0.03m diameter more than 5 diameters behind the rotor to eliminate tower shadow. The strut was strain-gauged to provide measurements of the axial force induced on the rotor. The blades, one of which was strain-gauged for out-of-plane bending moment at its root, were attached to an instrumented hub equipped with radio transmission of the bending moment signal to a fixed antenna in the rotor nacelle. The nacelle also contained an electromagnetic brake to provide constant torque rotor speed control. Further details are given in [2]. Apart from some measurements to help validate the numerical predictions the study focused on effects of unsteady uniform incident flow on the rotor loading as a simplification of unsteady flows associated with either incident flow turbulence or wave action from the surface. Oscillatory relative incident flow was generated by supporting the rotor from a computer controlled carriage above the flume which followed a sinusoidal motion, oscillating the rotor streamwise in a mean flow of 3% turbulence intensity and 5% mean flow variation. Measurements of axial force on the rotor and blade root bending moment were taken and compared with the numerical simulations for the same relative velocities (or current numbers) and these comparisons will be discussed.

Effects of dynamic inflow.

The numerical code was used to examine the effects of impulsive changes in incident velocity and correspondingly impulsive changes in blade pitch. These step changes were scaled to give asymptotic long-time matched conditions of axial force or induction velocity. Rapid changes in pitch are known to generate considerable overshoot in force due to the strong effect of dynamic inflow (lag of wake induced velocity) but a much smaller overshoot is observed for impulsive changes in incident velocity. A typical comparison from the present simulations is shown in figure 2. The reason for the difference can be understood from the wake induced velocity fields which have been extracted separately from the whole velocity field in the numerical simulations, and will be discussed.

Distortion of incident turbulence.

Because both surface wave effects and turbulence in the tidal stream are of a scale which is not very large compared with the scale of the rotor (or for multi-turbine deployments the array) both incident fields are distorted by the resistance of the rotor. Wave diffraction has been extensively studied for large marine structures. Less extensively distortion of turbulence by the mean velocity strain field of a body has been analysed by rapid distortion theory (RDT). Homogeneous distortion as in wind-tunnel contraction flow was analysed in [3] and non-homogeneous distortion by the flow field of a bluff body in [4]. Effects of weak non-homogeneous strain due to flow through a porous plate were investigated in [5]. All demonstrated significant effects of distortion on turbulence length scales smaller than the length scale of the body. Tidal stream turbines generate a flow field similar in the mean to a porous disc and therefore similar distortion effects may be expected. Detailed computation of non-homogeneous distortion involves numerical evaluation of many multiple integrals over the flow field, is computationally very expensive and not practical. Actuator disc theory approximates rotor flow 1-dimensionally and allows homogeneous strain analysis to be a good approximation for smaller length scales. Being the opposite of a contracting flow the mean strain increases the axial velocity component in the turbulence while decreasing the cross-stream components. This effect increases significantly the amplitude of unsteady tidal turbine rotor loading as discussed in [6], 1-dimensional RDT results for a horizontal axis rotor being presented in [7]. The present work presents similar analysis indicating increases of order 20% on loading and will be discussed together with a further development of the analysis for the frequency spectrum of the distorted flow.

Summary of Conclusions.

Numerical simulation supported by experimental code validation has demonstrated and analysed the much smaller effects of dynamic inflow due to rapid change in flow velocity compared with rapid blade pitch change.
Theoretical analysis has indicated that the effects of rapid distortion of incident turbulence by the mean flow field of the rotor can significantly increase the streamwise velocity fluctuations at the rotor particularly at low frequency.

References:

[1] Katz, J. and Plotkin, A. (1991). *Low Speed Aerodynamics*, McGraw-Hill.
[2] McNae, D. M. (2014). Unsteady Hydrodynamics of Tidal Stream Turbines. *PhD Thesis, Imperial College London.*
[3] Batchelor, G. K. and Proudman, I. (1954). The effect of rapid distortion of a fluid in turbulent motion. *Q. J. Mech. Appl. Maths , Vol. 7, 83-103*.
[4] Hunt, J. C. R. (1973). A theory of turbulent flow round two-dimensional bluff bodies. *J. Fluid Mech., Vol. 61, 625-706*.
[5] Graham, J. M. R. (1976), Turbulent flow past a porous plate. *J. Fluid Mech., Vol. 73, 565-591.*
[6] Milne, I., (2014), *PhD Thesis, University of Auckland.*
[7] Farr T.D. and Hancock, P.E., (2013), Torque fluctuations caused by upstream mean flow and turbulence. *Internal report to SuperGen Wind II (EPSRC) Consortium.*

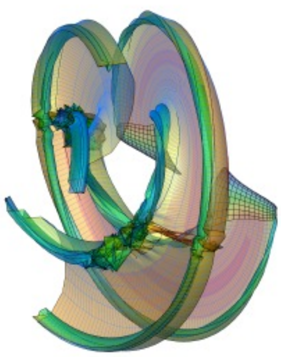

Figure 1 Rotor Wake.

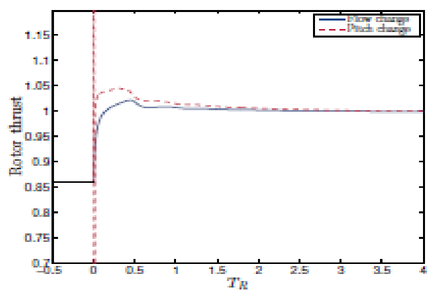

Figure 2. Rotor axial force due to impulsive pitch and velocity changes.
(TSR = 4.0 at T_R = 0.0, $\Delta\alpha = 2^o$, ΔU = 8%.)