Wave Induced Loads and Kinematics for Turbine Support Structures in Turbulent Flow

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Summary: A series of experiments has been conducted to assess the magnitude of turbine loads due to waves relative to those due to turbulence only and to determine the characteristics of the flow incident to downstream turbine locations. The distribution of thrust force on a single rotor in turbulent flow is fitted to an extreme value distribution and the modification due to opposing waves determined. The flow-field downstream of a single turbine and a fence of five discs is also studied to inform the loading on downstream turbines.

Introduction

Unsteady loads due to turbulence and due to waves are important design consideration for developers of tidal stream turbines and their supporting infrastructure. For isolated turbines the prediction of such loads is dependent on characterisation of the ambient flow and on the mode of operation of the turbine. In particular, above rated power pitch or stall control may be employed to limit mechanical loads. Blade and rotor loads have been analysed by blade element momentum theory, CFD, and laboratory experiments (e.g. [1-3]) typically with low values of onset turbulence. For turbines within arrays, the incident flow may be dependent on the wake of other turbines within the array and wave conditions may vary as they propagate across farms. Numerical and experimental studies of wakes have shown dependence of recovery on ambient turbulence characteristics [4] and numerical approach [5] but there have been limited studies of the influence of waves on the flow field downstream of turbines. The present study addresses the influence of waves on the loading and resultant wake of turbines that are subject to a flow with turbulence representative of a tidal stream site. Loading is studied for a single turbine and the downstream flow considered for both a single turbine and a small fence.

Experimental Arrangement

Time variation of wake velocity and of the corresponding thrust force were measured on model tidal turbines of diameter D = 0.27 m in water depth h = 0.45 m due to a turbulent flow and due to the same flow with opposing waves. The arrangement was similar to earlier studies by the authors [6] with turbine represented using a single three bladed rotor and up to five identical porous discs with porosity selected to develop the same thrust coefficient. The rotor or central disc was located at mid-span of an open channel of width 5 m and depth 0.45 m and 6 m downstream of a porous inflow weir and 6 m upstream (and upwave) of a line of flap type wave paddles. For all cases, the mean velocity of the flow is 0.46 m/s. At hub height (mid-depth), the flow had turbulence intensity of 12% and streamwise length scale was in the range 0.25-0.267 m. Waves generated had wavelength $L = 4.5h$ to $6h$ and amplitudes of $A = 0.035h$ to $0.08h$.

Rotor Loading

For a single turbine the mean thrust due to waves opposing turbulent flow was within 2% of the mean thrust due to flow only. An extreme value analysis was conducted to obtain the magnitude of thrust with 1 in N probability of exceedance. The peak force F_i during n = 1 to N independent events during a record of $0 < t < M$ is identified. The probability of exceedance of a given force is then $P(F > F_i) = n(F > F_i)/N$. Alternative extreme value distributions were compared and sensitivity to threshold force and sample interval analysed to obtain convergence to within 3%. The 0.1% load due to turbulent flow was found to be 50% greater than the mean thrust. The extreme values due to waves and turbulent flow were found to depart from the turbulent thrust distribution and exhibited a quadratic growth with velocity amplitude. It is found that a reasonable prediction of the extreme forces due to both turbulence and waves is given by superposition of a drag force with drag coefficient of 2 based on the wave particle velocity only and with an unchanged mean thrust coefficient of 0.89 for the turbulent flow.

Wakes and Waves

Measurement of velocities downstream of a single rotor showed the periodic wave-induced fluctuations altered the depth profile of both mean velocity and total kinetic energy of the flow (here denoted FKE) within 4D downstream (Fig. 1). As might be expected the depth over which the wake velocity profile was altered is dependent on the wave depth parameter kh. The superposition of waves was also found to increase the rate of recovery of mean velocity along the axial centreline to a distance of 10D downstream. Measurements within the wake of multiple turbines show very similar wake profile and recovery rate without and with waves. In part this is due to a reduction of wave height over the reduced velocity region downstream of the turbines (Fig. 2). This is attributed to wave refraction across the transverse shear profile that exists between the wake and bypass flow. Preliminary analysis of this process using the spectral wave model SWAN will also be presented.

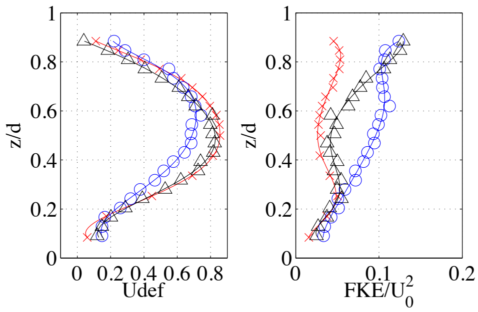

Figure 1: Depth profile of velocity deficit and of kinetic energy of the flow (turbulent and wave induced) measured 2 Diameters downstream of a 3-bladed rotor with thrust coefficient 0.89 and tip speed ratio 5.5. (x - No Wave, o – kd=1 and Δ - kd=3.13)

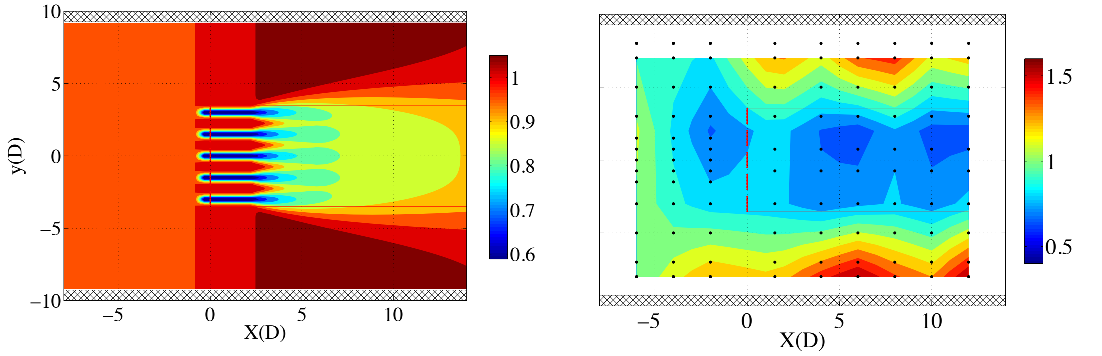

Figure 2: Velocity deficit field (left, 1-U_x/U_0) from empirical wake model and change of significant wave height (right, H_s/H_{s0}) in vicinity of a row of five discs. Disc are at centre to centre spacing of 1.5D with central disc at (x,y) = (0,0).

Conclusions

Load and flow measurements from scale experiments using a rotor, discs and a wide channel have been analysed to understand the extent to which turbine loading may be influenced by waves at tidal stream sites. The thrust exceeded with probability 1 in *N* was analysed for turbulent flow only and with waves. A reasonable prediction of the load distribution in waves is given by the turbulent load distribution superposed with a drag force based on the wave-induced kinematics only. Downstream of a single turbine waves are observed to increase the total kinetic energy to a depth dependent on the wave depth parameter. This modifies the depth profile of velocity through the turbine centreline, particularly near the surface, and slightly alters the rate at which velocity recovers to the far-wake deficit. For multiple turbines, waves are reduced over the wake region and so the wake characteristics are comparable both without and with waves.

References:

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