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Experimental study of extreme thrust on a tidal stream rotor due to turbulent flow and with opposing waves

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ABSTRACT

Time-varying thrust has been measured on a rotor in shallow turbulent flow at laboratory scale. The onset flow has a turbulence intensity of 12% at mid depth and a longitudinal turbulence length scale of half the depth, about 5 times the vertical scale, typical of shallow flows. The rotor is designed to have thrust and power coefficient variations with tip speed ratio close to that of a full-scale turbine. Three extreme probability distributions give similar thrust exceedance values with the Type 1 Pareto in mid range which gives 1:100, 1:1000 and 1:10 000 exceedance thrust forces of 1.38, 1.5 and 1.59 times the mean value. With opposing waves superimposed the extreme thrust distribution has a very similar distribution to the turbulent flow only. Exceedance forces are predicted by superposition of a drag force with drag coefficient of 2.0 based on the wave particle velocity only and with an unchanged mean thrust coefficient of 0.89. These values are relevant for the design of support structures for marine turbines.

1. Introduction

Tidal stream turbines are being designed to convert energy from tidal flows into electricity. Several prototype turbines have demonstrated the potential of this technology with rated power of around 1 MW. Planning is ongoing for arrays of turbines at various sites including in the Pentland Firth (Scotland), the Skerries (N Wales), the Bay of Fundy (Canada) and near Brittany (France). Most of the turbines in development are superficially similar to wind turbines, typically with a horizontal axis and two or three blades. However rotor diameter is limited by the water depth and tidal turbine blades typically have smaller aspect ratio (chord/blade length) and greater thickness due to high root bending moments. Turbulence in tidal flows is also quite different from that in wind for which an unbounded turbulent boundary layer is applicable. Tidal flows are bounded by the water surface and this causes horizontal length scales to be many times the vertical which are typically about 10% of the depth as suggested by Prandtl (1927). Horizontal length scales of about half the water depth are typical of shallow flows; for example this has been demonstrated for wakes in Stansby (2003).

The rotor and blade geometry of a tidal turbine are generally designed using blade element momentum theory, combining force coefficient versus angle of incidence for typical hydrofoil geometries with momentum theory to determine variation of power and thrust coefficient with tip speed ratio. This is quite successful and can be formulated for quasi-steady onset flows due to wave-induced kinematics and for dynamic problems such as electrical fault (Moriarty and Hansen, 2005; Bossanyi, 2007; Masters et al., 2011). Computational fluid dynamics (CFD) has provided more detailed information, particularly with regard to loading due to turbulence (Afgan et al., 2013), blockage effects (Nishino and Willden, 2013) and

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the wake structure (Churchfield et al., 2013). Experimental studies have demonstrated the effect of unsteady onset flow on thrust, power and blade loads. Thrust variation of a constant speed turbine has been analysed due to homogenous turbulence and waves (Gaurier et al., 2013) and due to channel turbulence (Chamorro et al., 2013). However limited attention has been given to extreme loading despite the importance of this for support structures and blade design. In this study, laboratory scale experimental measurements are reported and analysed to assess extreme thrust characteristics. This also gives some indication of extreme blade loads although they are not directly measured. We consider turbulent flow over a smooth bed within a wide channel. The effect of superimposed opposing waves is also analysed. Although turbines are often shutdown with wave heights above a certain threshold smaller waves affect power generation and loading and hence extreme loading.

2. Experimental conditions

Experiments were undertaken in the wide flume at University of Manchester, 5 m wide with a water depth $h = 0.46$ m giving a scale of around 1:70 compared to a tidal site of approximately 30 m depth. The mean flow speed at hub height U_0 was 0.46 m/s and the design of rotors for this laboratory scale is described below. The flume has a conventional design with deep chambers at either end connected by two large diameter pipes located beneath the flat bed and containing axial flow turbines. A vertical mesh was placed across the inlet to the horizontal bed to break up the large-scale structures resulting from jets entering a chamber. The rotor plane was located at 6.0 m from the inlet and the velocity field was analysed at this location prior to tests with the rotor installed. The rotor axis was positioned at mid-depth and mid-span.

2.1. Flow measurement

Time varying velocities were recorded using NORTEK Vectrino+ ADV probes with velocity range $\pm 100\ \text{cm s}^{-1}$, sample volume of 3 mm and transmit length of 8.7 mm. These settings returned signal to noise ratio SNR > 15 dB and correlation coefficient COR > 90% for the majority (> 95%) of samples. Velocity was sampled at 200 Hz, sufficient to resolve the channel turbulence to the dissipation range (Nezu and Nakagawa, 1993, p. 30). Probes are positioned in the cross-stream y–z plane by an automated traverse table with position accuracy of 1 mm and the carriage is located manually in the longitudinal x-axis. Longitudinal mean velocity U_0 and turbulence intensity u'_{rms}/U_0, where u' is fluctuating velocity, were obtained from samples of time-varying longitudinal velocity $u(t)$ obtained from a single probe. Longitudinal turbulence length scale L_{uu} was obtained from auto-correlation R_{uu} of the measured velocity applying the frozen turbulence assumption:

$$L_{uu} = U_0 \int_0^{\infty} R_{uu} d\tau, \tag{2.1}$$

$$R_{uu} = \frac{u'(t)u'(t+d\tau)}{u'(t)^2}. \tag{2.2}$$

The velocity profile measured at the rotor plane is shown in Fig. 1 along with the longitudinal turbulence intensity, which is fairly constant at about 12%. The length scale at mid depth is 0.267 m, or 59% of the water depth. Turbulence length scales

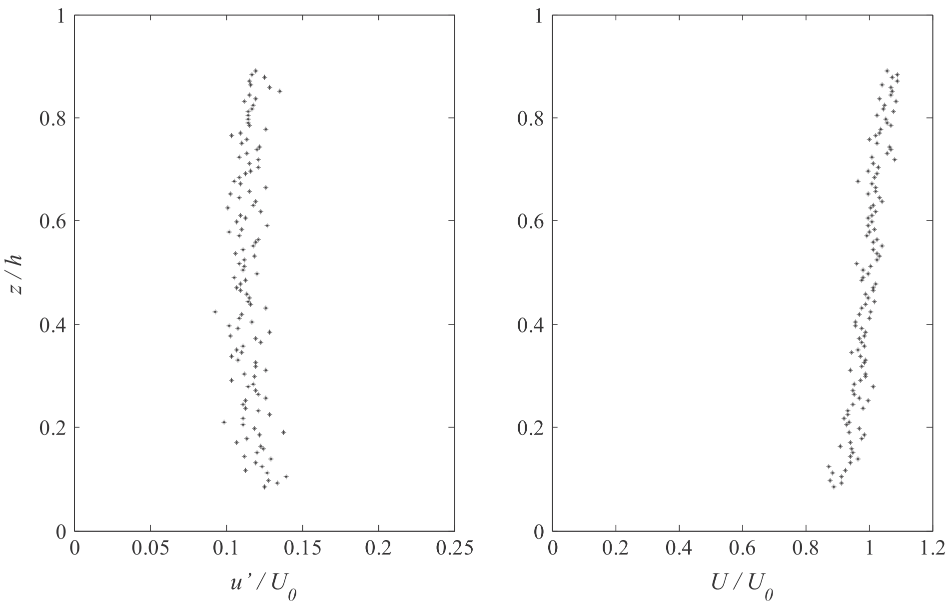

Fig. 1. Depth variation of turbulence intensity u'/U_0 and normalised mean velocity U/U_0 for channel flow at rotor axis. Obtained from 1 min samples.