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Blade loads on tidal turbines in planar oscillatory flow

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ABSTRACT

Characterisation of the unsteady hydrodynamic loads is essential for accurate predictions of the fatigue life and ultimate loads of tidal turbine blades. This paper analyses a set of experimental tests of the hydrodynamic blade root out-of-plane bending moment response to planar oscillatory motion, chosen as an idealised representation of the unsteadiness imparted by waves and turbulence. Phenomena associated with dynamic stall are observed which are sensitive to the oscillatory frequency and velocity amplitude. Flow separation is shown to result in loads significantly greater in magnitude than that for steady flow. Following flow reattachment, the load cycles compare relatively well with Theodorsen's theory for a two-dimensional foil oscillating in heave, suggesting that circulation due to the shed wake dominates the unsteadiness in phase with acceleration, over added mass effects. For attached flow, the effect of unsteadiness is comparatively much smaller. At low frequencies a phase lead over the velocity is observed, compared to a lag at higher frequencies. Multiple frequency oscillations are also briefly considered. Reconstruction of the multi-frequency response using both the steady flow measurements, and the single frequency measured response, is shown to offer a relatively good fit when the flow is attached, for lower frequency combinations.

1. Introduction, critical review and aim

Unsteadiness in the onset flow is a dominant driver of both ultimate and fatigue loads of tidal turbine blades, which arises from the phenomenon such as turbulence, surface waves, and the depth-wise variations in the mean flow. Characterising these loads is crucial if tidal turbines are to meet their intended service life of at least 20 years and prove to be economically competitive with other renewable energy technologies. The vast majority of the literature has been, however, predominantly focused on characterising the steady thrust loads for tidal turbines, with the flow attached across the blades (see Bahaj et al., 2007a,b; Myers and Bahaj, 2006, 2007). Unsteady loading, particularly on the blades, where acceleration effects cannot be neglected, is inherently more complex and comparatively much more poorly understood. This is due, in most part, to the difficulties in performing experiments at sufficiently large scale to permit the underlying unsteady hydrodynamics to be accurately studied. The lack of confidence in describing the unsteady loads has unsurprisingly resulted in industrial design standards for tidal turbines currently not yet having rigorous methodologies available for analysing unsteady loading. Designers of turbine blades subsequently have limited guidance in assessing the ultimate loads and fatigue. As reported by Marsh (2009), this has led to significant levels of over-conservativeness being employed in early generation devices, which ultimately must be reduced.

The objective of this present study is to experimentally analyse the out-of-plane blade-root bending moment (defined as being about an axis normal to the rotor axis) response to harmonic axial motion, deemed representative of the free-stream velocity perturbations induced by the unsteady flow. The response to harmonic oscillatory motion is of interest for various reasons. Stochastic approaches are typically employed in fatigue calculations, and the application of an inverse Fourier analysis can lead to the computation of the impulse function itself which is very difficult to experimentally obtain, and which can be used to develop time domain based simulation models. By comparing the unsteady bending moment histories with reconstructions using the loads acquired for steady flow, as well as from theoretical predictions of oscillating airfoils, an attempt is made to quantify the relative influence of flow acceleration and subsequently the various underlying unsteady hydrodynamic load constituents. This will assist blade designers in evaluating the level of complexity required in their load prediction models, as well as providing a useful data set from which to validate and improve existing models.

The unsteady hydrodynamic blade loads arise from both circulatory and non-circulatory phenomenon. Leishman (2002) suggests that the circulatory forces are associated with the response of the induced velocity from a combination of vorticity contained in the shed wake at the blade element, and circulation in the trailed wake. The trailing wake component is considered to dominate at

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low frequencies, and is associated with a dynamic inflow effect. The interaction between the shed wake and dynamic inflow effects is complex but each contribution is typically treated separately, due to dynamic inflow having a longer time scale of 1–1.5 rotor revolutions compared to 0.1 rotor revolutions for the shed wake phenomenon. The non-circulatory or true added mass forces are present due to the pressure forces which are required to accelerate the fluid in the vicinity of the blade element. This results in a force which opposes the acceleration of the flow, and therefore a positive out-of-plane bending moment. As Whelan (2010) discusses, the added mass effect is likely to be more significant for tidal turbines compared to wind turbines, as the fluid and structural densities are of the same order of magnitude. In unsteady flow the stall behaviour can also differ significantly from the steady flow cases; in that the separation and reattachment of the flow occurs at higher and lower effective angles of attack respectively, and results in large loads. Leishman (2006) discusses that dynamic stall is highly non-linear and is typically associated with both a dynamically induced camber effect, which acts to delay trailing-edge separation, and the formation and shedding of a leading edge vortex, which induces a pressure wave over the upper surface of the airfoil and subsequently leads to larger normal forces.

Experiments reported by Maganga et al. (2010) provide an insight into the general response of a tidal turbine exposed to fluctuating thrust resulting from unsteady flow. An increase in the mean thrust load on the structure of approximately 15% was observed at typical operating states, as the turbulence intensity of the flow in a flume was varied from an ambient 8% to 25%. However, the spectral characteristics of the unsteady flow and dominant length-scales were not reported, and it is therefore difficult to infer the corresponding full-scale loading. Galloway et al. (2010) have also reported on experiments on a tidal turbine, towed at constant velocity in a still-water tank and subjected to surface waves. Whilst the blade loads, again, were not specifically studied, for relatively small waves of approximately 1.6 m full-scale, the cyclic shaft thrust range was relatively large and of the order of 37% of the mean. For horizontal axis tidal turbines, which are the focus of the study here, the fluctuations in the individual blade loads can also be much more severe than the rotor thrust loads, which tend to average out the unsteady blade loads when the flow is non-coherent across the rotor.

Inferring the hydrodynamic loading on the rotor from shaft measurements, however, has the additional complication that the contributions from the shaft and hub inertia, as well as bearing friction, must be accounted for. As is the case for the experiments performed in the present study, Barltrop et al. (2006) used instrumented blades to directly measure the blade-root bending moment response. They reported on a set of experiments in a still-water towing tank, in which the forward speed of the carriage represented the mean velocity of the current, whilst the turbine was subjected to velocity perturbations resulting from surface waves. The dynamic load amplitudes were found to be 50% and 100% of the mean, in the out-of-plane and in-plane directions respectively. For relatively linear waves and attached flow, the bending moment time histories were found to compare reasonably well with a quasi-steady numerical, blade-element momentum model, with no acceleration effects included. This again suggests that unsteady influences were relatively small. Under such conditions the incident flow is therefore relatively uniform over the rotor and suited to planar oscillatory tests.

Whelan (2010) conducted an experimental investigation of the dynamic thrust response of a 300 mm diameter scale tidal turbine to harmonic axial motion, in an attempt to establish the magnitude, and relative contributions of true added mass and dynamic inflow for attached flow. The experiments were performed by surging the turbine test rig on a carriage in a flume and measuring the thrust load on the support structure. This motion, as is the case for the experiments presented in this paper, was considered to induce an oscillatory heaving motion on the blade section. It was found that the total axial inertia effects were considerably smaller than the unsteady thrust in-phase with velocity, but comparable to the solid inertia and were therefore important for control and fatigue calculations. Whilst Whelan's study showed promise, the experimental test rig was subject to a variety of complications (speed control, etc.) and the use of a rather small flume resulted in high blockage factors which could have compromised the results. As true added mass and dynamic inflow both act in-phase with the acceleration, it was not possible to separate the two effects experimentally at the frequencies considered. Comparisons were subsequently made with linear unsteady airfoil theory of Theodorsen (1935), and the returning wake extension by Loewy (1957), in which the circulatory term was considered to be associated with dynamic inflow. These suggested that, at the model scale employed, the magnitude of the contribution from the two effects were approximately equal, but the circulatory estimates tended to be less applicable to full-scale devices, for which a lag was instead predicted.

The authors are unaware of the literature directly pertaining to dynamic stall of tidal turbines. Insight into the phenomenon associated with stall is instead directed to works in the helicopter and wind turbine contexts (see Shipley et al., 1995). The majority of the experimental studies used to infer dynamic stall phenomenon involve wind tunnel tests of 2-D airfoils typically oscillating in pitch, with relatively limited literature available for heaving motion. Pitch oscillations of the NREL S814 airfoil, used in this experiment, were reported by Janiszewska et al. (1996). They have shown the maximum lift coefficient to be up to 110% higher than the steady-state value for a $\pm 10^{\circ}$ oscillation in angle of attack.

Several relevant issues are cited by researchers, following their investigations of dynamic stall. Leishman (2006) discusses that the response can differ between forcing conditions for the equivalent effective angle of attack. This is considered to be due to pitch oscillations giving rise to a lower leading edge pressure gradient compared to oscillations in heave, such that the conditions which instigate separation are experienced at higher angles of attack. Hansen et al. (2004) have commented that leading edge separation is typically not a dominant phenomenon for thick airfoils such as those used on wind turbines, which is also likely to be the case for tidal turbine foils. The effect of three-dimensionality on the stall process for a rotating wind turbine blade at a Reynolds number of 300,000 was investigated by Barnsley and Wellicome (1992). Delays in the loss of the leading edge suction peaks were observed, which resulted in enhanced lift incidence over 2D behaviour. Du and Selig (1998) have also reported on finding a slight delay in separation for a rotating blade, leading to increased lift. The events associated with dynamic stall have proved challenging to model. The frequently cited Beddoes–Leishman model (see Leishman and Beddoes, 1986, 1989; Hansen et al., 2004, specifically for wind turbines airfoils) combines Theodorsen's model for the unsteady attached flow dynamics, with empirical models for the delay in separation and movement of the vortex. If empirical models are to be employed by tidal turbine designers there is an apparent need for experimental data of dynamic stall events of tidal turbines blades for validation purposes.

1.1. Aim

Tidal turbine developers need to establish the operating conditions in which the unsteady loads become significant and dynamic stall is likely to be instigated, and subsequently the load ranges which result. The likely errors which may be incurred by using a quasi-steady