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Quantifying turbulence from field measurements at a mixed low tidal energy site

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ABSTRACT

This study explores typical characteristics of the mean and turbulent profiles at a mixed low tidal energy site (40 m mean water depth) where the waves have limited effects on the currents. The turbulence profiles were derived from secondary current data using a 5-beam ADCP which was optimised for wave measurements. The tidal currents have peak flows of ~1 m/s during spring tide. The turbulence intensity is no less than 10% at peak flows and compares well with values at other tidal channels (at ~5 m from seabed). The Reynolds stresses show symmetry at the neap tide but less so for the spring tide. Although the qualitative profiles of TKE are similar between the neap and spring tides, the values of TKE for flood flow are the largest throughout the deployment. The integral length scales are in good agreement with theory, and with estimates based on the mixing length concept. The measured turbulence parameters are sensitive to flow inhomogeneity, Doppler noise, and ADCP tilt. The findings demonstrate the practical benefits of exploiting secondary current data at a mixed low tidal energy site for estimating typical turbulence characteristics; such information can be used to define design standards and protocols for marine energy devices.

1. Introduction

Knowledge of field turbulence is important for wave and tidal energy converters since turbulence can affect the dynamic response of components (e.g. transient and fatigue loadings [1], resonance) as well as the quality of extracted power. Marine structures are sometimes unnecessarily over designed due to a lack of understanding of turbulence effects at sea [2]. Turbulence has also an impact on dynamic processes such as mixing, sediment transport and energy dissipation, all vital for fluid structure interactions and marine ecology. However, characterising turbulence from field measurements is not trivial: skilled scientists and operators are often needed to setup, deploy and recover sensors [3], the deployment costs are high, and there is the difficulty of interpreting non-filtered, random raw measurement data. No adequate procedure or equipment yet exists for measuring the full range of temporal and spatial scales of field turbulence. There are sensors that exploit current velocity measurements to derive turbulence data. One of these is the Acoustic Doppler Velocimeter (ADV) which estimates the three-dimensional current velocity field over very small water volumes, at high sampling frequencies e.g. 10–20 Hz. However, the use of ADV is limited to a point measurement and cannot offer estimates over a water column. In addition, devices such as hot-film current meters and shear profilers require repeated challenging measurements, leading to expensive deployments before one is able to obtain useful time series. In contrast, the use of self-contained, moored Acoustic Doppler Current Profilers (ADCPs) offers non-intrusive, combined measurements of waves and currents throughout a full water column for long periods of time with relatively straightforward deployment operations. With ADCPs, if one is interested in turbulence along a water column the instrument itself does not generate any extra turbulence as a result of its setup (which only requires a frame), compared with other ocean setups in which the instruments can cause extra turbulence. Few recent studies have looked into the measurement of field turbulence using ADCPs, ADVs or a combination of both. Particularly at tidal sites, field turbulence has been characterised at the European Marine Energy Centre (EMEC) at Orkney Islands ([3,4]), the Sound

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of Islay, UK [5], the Puget Sound off the west coast of Washington [6], the East River in New York [7], and more recently a 2-month turbulence measurement campaign using ADVs at Roosevelt Island Tidal Energy site, NY, USA [8]. In comparison, however, field studies that report turbulence measurements at mixed energy sites remain scarce. This paper is a contribution towards providing field turbulence data at a wave energy site, with tidal currents, based on the use of ADCP.

To resolve the range of scales of turbulence at a marine energy site using ADCP's current velocity measurements, optimum settings are required in terms of instrument frequency, power consumption, bin size, minimum disturbance to the flow, and ADCP sampling frequency. However, optimum settings are not always at the disposal of researchers. To our knowledge, it is not yet possible to have the ADCP setup for accurate measurement of both waves and currents; it can only achieve high accuracy for one measurement type. Common practice indicates that ADCP deployments at wave energy sites are optimised for wave measurements only, rarely considering the practical benefits of estimating some turbulence parameters from the combined current data. This fact is a motivation for writing this paper: since high resolution ADCP velocity data from field measurements are difficult to obtain, even a limited characterisation of turbulence from non-optimum ADCP setups could provide valuable data to support the development of marine energy devices. In general, because of the advantages of using ADCPs, it is important to steer users' interest towards maximising the amount of useful information derived from combined wave and current measurements. This can be achieved via developing advanced post-processing techniques as in Ref. [9], or deriving turbulence metrics from the measured currents as in the present investigation. Studies of currents (at wave sites) are useful for quantifying wave–current interactions as shown in the studies of Hashemi et al. [10] and Lewis et al. [11]. It is worth noting that the Wave Hub site has very little in terms of interactions between the waves and the currents such that the measured turbulence profiles may be considered to experience limited effects from the waves. The reported measurements present a contribution to the growing number of field studies characterising flow and turbulence at marine energy sites and as such add to the knowledge from other, similar studies. The paper seeks to demonstrate the capabilities of a 5-beam ADCP for characterising field turbulence when the unit is optimised for waves. The key question addressed in the paper is: Can acoustic Doppler profilers be used to derive typical turbulence characteristics in a mixed site with limited wave current interactions using a non-optimum setup?

2. Field measurements, data collection and processing

The data investigated in this study come from field deployments near the UK's marine energy Wave Hub site, situated in the Bristol Channel, approximately 16 km off the north coast of Cornwall (UK), for the period of 12–23 October 2010 (the ADCP location is at 50°18′38″N, 5°40′32″W). A map of the deployment location is shown in Fig. 1 where the ADCP was co-located with four directional wave buoys. The deployment encompassed the period of one full neap tide and the majority of one spring tide. Two other deployments were performed in the period August–October 2011 but they are not discussed here. The UK's Wave Hub has been commissioned to provide a shared testing facility to assist with the commercial demonstration of wave energy converters by means of a subsea, grid connected electrical hub (www.wavehub.co.uk). It is expected the site will provide an electrical capacity of 20 MW, with a possible upgrade to 50 MW over a 25 year period. The deployment site has considerable wave energy potential; an annual mean power density in the range of 16.9 kW/m (over 2001–2005) and 29.9 kW/m (over 1989–1998) has been reported in the study of Smith et al. [12]. Research reported in this paper supports the commercial development of the Wave Hub through field assessments of the wave and tidal resources, as well as the effect of their mutual interactions on marine energy components (e.g. wave energy devices, offshore wind turbines). Because of the potential for developing wave energy at the site, the ADCP was optimised for measuring surface gravity waves, not currents. As illustrated in Fig. 1, the original scope involved the deployment of an RDI Teledyne ADCP in the proximity of an array of four directional wave buoys, for the purpose of comparing the wave measurements from the two sensors; some aspects of this work are discussed in the field investigation of Strong et al. [13]. It turned out that the wave climate at the deployment site is also affected by tidal currents [14] with 4–5 m tidal level variations and ~1 m/s maximum current velocity. However, as demonstrated in Colucci et al. [15,16] there is very little in the way of interaction between waves and currents at this particular site and so the turbulence metrics can be assumed to experience limited effects from the waves. Although this paper focuses mainly on current measurements, time series of significant wave height H_S, peak period T_P, peak wave direction D_P and water level variations during the deployment period are shown in Fig. 2 for reference. More details about the wave aspects are found in the studies by Strong et al. [13] and Saulnier et al. [14].

ADCPs rely on the principle of “Doppler shift” of the acoustic signals reflected off tiny particles to get an estimate of the water velocity. With an ADCP, the water column is discretised into a number of bins at the centres of which current velocities are estimated, resulting in a vertical velocity profile. The 300 kHz ADCP was deployed on the sea floor in a purpose-built mooring frame, looking upwards in a mean water depth of 40 m. Single ping measurements were used in order to reduce bias in the turbulence measurements (i.e. reduced temporal resolution) as opposed to averaged sub-pings, e.g. mode 12 used with RDI ADCPs. The main deployment parameters for waves and currents are summarised in Table 1. An illustration of the 5-beam ADCP, including a definition of the axis system and geometrical angles, is shown in Fig. 3.

Compared with the standard 4-beam “Janus” configuration, the present 5-beam ADCP has an additional vertical 5th beam, used for high resolution direct surface tracking of the waves. The four inclined beams perform two functions: 1) estimation of directional wave spectra from the wave-induced orbital velocities, and 2) measurement of the along-beam current velocity throughout the water column. The uniform bin size used by the inclined beams was 4 m, which is large but this was set to force low variance orbital velocities for accurate estimates of directional wave spectra [17]. Unfortunately, this also fixed the bin size for current measurements to 4 m, from which turbulence metrics were derived. In comparison, it is customary to use small bins of 0.5–1.0 m for current measurements but at the time of the field study the ADCP could not be setup with different bin sizes for waves and currents. In terms of the focus of the paper, this setup is likely to limit the turbulent spatial scales that can be resolved from current measurements. It can be argued, however, that quantities such as Reynolds stresses and turbulent kinetic energy (TKE) mainly depend on the large scales of the flow [18] and as such may not require the smallest scales to be resolved. Available ADCP types cannot accurately measure turbulence quantities that depend on the smallest scales of the flow. To fully resolve such scales, it is required that the sensing volume is smaller than the smallest scales of the flow [19,20]. In addition to the spatial scales, the 2 Hz sampling frequency used by the ADCP means that the time scales that can be resolved are limited to 1 Hz.

After recovery, raw ADCP current velocity data was processed using Teledyne RDI's BBList utility to obtain time series of velocities