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Quantifying uncertainty in acoustic measurements of tidal flows using a 'Virtual' Doppler Current Profiler

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ABSTRACT

Accurate characterisation of flows at tidal sites can enable the developers of tidal stream energy projects to design and model the loads on, and the performance of, tidal energy converters. Acoustic Doppler technology is versatile in the measurement of sea conditions; however, this technology can be limited in its effectiveness at measuring the small-scale kinematic fluctuations caused by waves and turbulence. A Virtual Doppler Current Profiler (VDCP) is used to sample a simulated tidal flow to understand the limitations of this type of measurement instrument whilst recording the small timescale kinematics of waves and turbulence in tidal currents. Results demonstrate the phase dependency of velocity measurements averaged between two acoustic beams and provide a theoretical error for wave and turbulence characteristics sampled under a range of conditions. Spectral moments of the subsurface longitudinal wave orbital velocities recorded by the VDCP can be between 0.1 and 9 times those measured at a point for certain turbulent current conditions, turbulence intensity measurements may vary between 0.2 and 1.5 times the inputted value in low wave conditions and turbulence length scale calculation can also vary hugely dependent on both current and wave conditions. The continuation of this work will enable effective comparison of a linear model for tidal flow kinematics against field measurements from UK tidal site data, and subsequently validate numerical models for the testing of tidal turbines.

1. Introduction

To optimise the design of tidal stream turbines, many of which will be exposed to sea conditions, robust design procedures are required. This includes the use of validated models to represent current kinematics in the presence of waves and turbulence for pre-construction site specific load calculations. Many early prospected UK sites such as the sound of Islay, Kyle Rhea (Neill et al., 2016a), and Strangford Lough (Neill et al., 2016b) were sheltered from ocean waves however tidal sites such as the Pentland Firth, Fairhead, and St David's suffer from wave heights which may reach extremes of up to 10 m. Impacts on the velocity profile by waves could reduce the theoretical tidal resource by 10% (Lewis et al., 2014), and have a significant effect on blade loads (Barltrop and Varyani, 2006), however this theory must be validated with field measurements of subsurface velocities.

This paper will focus on the characterisation of combined wave and turbulent current conditions at tidal races using Acoustic Doppler (AD) technology. AD technology is commonly used in measurement of subsurface velocities and sea surface elevation. Upward looking devices emit sound pulses from transducers which are reflected by particles suspended in the water column returning a signal to the instrument. The signal is frequency shifted (Doppler shift) according to the velocity in the pulse direction at which the particle was travelling. By emitting pulses at high frequency and trigonometrically transforming the resultant velocities in combination with two or three other transducer records, a three-dimensional velocity time-series can be calculated. The typical assumption is that the flow is homogeneous over the volume between the instrument's transducer beams (Lu and Lueck, 1999). This is effective for measuring a range of current conditions; however, the smaller fluctuations resulting from waves and turbulence can be obscured by this method (Nystrom and Rehmann, 2007). Improved methods have been published for resolving mean current (Gilcoto et al.,

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2009; Ott, 2002), turbulence (Gargett, 1994; Vermeulen et al., 2011; Wiles, Nov et al., 2006; Stacey et al., 1999; Stacey, 2003; Souza, 2010; Lohrmann, 1990; Guerra Paris and Thomson, 2017), and wave velocities (Filipot et al., 2013), however this paper focuses on using a conventional Doppler Current Profiler (DCP) configuration with the aim of improving site characterisation of wave and turbulence subsurface velocities by understanding its limitations.

In this study a 'Virtual' DCP (VDCP) is used to mimic field measurements taken by a generic DCP. Specifically, the study aims to quantify theoretical errors in measurements affecting the design of tidal turbines. Therefore, whilst a range of depths are considered in initial studies, under focus are those wave and turbulence induced velocities at turbine hub height. Velocity time series combining the effect of currents, turbulence and waves are simulated as described in Section 2.1. The VDCP samples ten-minute velocity time series using the commonly used Janus configuration; four transducers separated by 90 degrees in the horizontal plane, each at 25 degrees from the vertical, using the method covered in more detail in Section 2.2. Sampling of combined wave, current and turbulence simulations are presented in the results in Section 3 highlighting the difficulty in separating and characterising the different components within a flow. Section 4 summarizes some of the more critical effects at turbine hub height on measures of wave and turbulence characteristics in realistic combined wave-current flows.

2. Methodology

The methodology proposed here, incorporates a Virtual Doppler Current Profiler (VDCP) which is designed to be a numerical tool that mimics the measurement technique of a real DCP, instead sampling a simulated flow field, and quantifying the theoretical limitations of DCP subsurface velocity measurements.

2.1. Simulation of tidal flows

For this study velocity time series are generated at 1 Hz for ten minutes. The simulated tidal flow defines a velocity time series of specified length at any desired point within a grid of specified size, considering the velocities resulting from waves (U_{wave}), currents ($U_{mean\ flow\ shear}$), and turbulence ($U_{turbulence}$):

$$U_{total} = U_{meanflowshear} + U_{wave} + U_{turbulence} \tag{2.1}$$

The wave conditions, turbulence conditions and flow shear are simulated separately and combined linearly to form a time series of velocities generated at specified frequency. The turbulence field is generated prior to running the combined model on a grid of specified width, height and cell size. Turbulence is then applied to the model by taking the velocity time series from the nearest point. Decreasing cell size increases turbulence resolution, however increases computational time. Interpolation methods to estimate turbulence velocities at the designated point were found to be largely ineffectual, improving accuracy little due to the spatial coherence of the turbulence simulated. Subsequently the optimum cell size compromising between accuracy and computer time was found to be 1 m^2.

2.1.1. Flow shear

A mean flow shear profile, u, at chosen depth, z, is added; calculated using the mean velocity $\bar{u}$, at reference depth, z_{ref}, according to the specified power law profile:

$$u(z) = \bar{u}(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{2.2}$$

The exponent α is typically chosen to be 1/7, however a value of 0 can also be used to define a uniform current for some of the investigations described in this paper.

2.1.2. Waves

The irregular wave velocity field is defined using linear wave theory from a simulated omnidirectional JONSWAP (Hasselmann et al., 1973) sea surface elevation spectrum defined using significant wave height (H_s), mean period (T_m) and a peak enhancement factor of 1. The spectrum is given directionality using a cosine^{2s} directional distribution (Krogstad and Barstow, 1999) defined with power, s, equal to 1. The simulated spectrum is modified according to the strength and direction of the mean current ($\bar{u}$) with respect to the wave direction. The method takes into account current effects on the relative angular frequency and wavenumber, according to Hedges (Hedges, 1987). Therefore, if currents are included, the spectral density of the surface elevation, S_{η_M}, is modified to give the resultant spectrum, S_η, where g is acceleration due to gravity.

$$S_\eta = S_{\eta_M}\frac{\omega_a^2}{\omega_r^2}\left(\frac{1}{1+2\bar{u}\frac{\omega_a}{g}}\right) \tag{2.3}$$

Relative wave number, k_r and angular frequency, ω_r are calculated iteratively using the dispersion relationship according to Guo (2002), where ω_a is the absolute angular frequency, and $\bar{u}$ is the mean current velocity in the wave direction.

$$\omega_r = \omega_a - k_r\bar{u} \tag{2.4}$$

The spectrum of the stream-wise velocity and the vertical velocity are derived from the surface elevation spectrum using linear wave theory (Mackay, 2012), depending on the height of the water column, the required depth, and the wave direction relative to the current. A velocity time series is calculated using an inverse Fourier transform of the velocity amplitudes derived from the velocity spectrum with phase calculated according to wavenumber, and location.

No stretching (i.e. Wheeler (1969)) has been included to take account for changes in water particle velocities due to deformation of the sea surface. Tidal turbines will tend to avoid at least the top 5 m of the water column due to severe impact from waves. Furthermore, side-lobe interference in 'real' DCPs will render much of the data in this part of the water column unusable. It is therefore not deemed necessary within the scope of this work to account for changes due to proximity to the sea surface.

2.1.3. Flow turbulence

Turbulence can be included in the current field model and is synthesised, prior to running the combined flow model, numerically using the "Sandia method" for simulating 3 dimensional flows, described in Veers (1988). A turbulent time history is generated for the current field on a grid of equally spaced points in a 2D plane which spans the y and z-axes. The time history of velocities in three dimensions is generated for each of these points such that each point has correct spectral characteristics and each pair of points has the correct coherence and cross-spectral characteristics. For example, for the stream-wise component of velocity (u), the coherence (C_u) of points separated by distance (Δr) is a function of η_u which is defined using the local length-scale (L_u) and the wave number (k) calculated for a range of frequencies (f) at mean current speed ($\bar{u}$). Further detail can be found in appropriate turbulence texts (Tennekes and Lumley, 1972).

$$\eta_u = \sqrt{\left(\frac{0.747\Delta r}{2L_u}\right)^2 + (70.8\ \Delta r\ k)^2} \tag{2.5}$$

The longitudinal local length scale (L_u) is calculated using lateral and vertical components of longitudinal length scale (${}^yL_u$ and ${}^zL_u$) , as well as the lateral and vertical separation of the points (dy and dz).

$$L_u = \sqrt{\frac{({}^yL_u dy)^2 + ({}^zL_u dz)^2}{dy^2 + dz^2}} \tag{2.6}$$