The use of Doppler Sensor Arrays to Characterise Turbulence at Tidal Energy Sites

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Abstract

Newly collected data from a mid channel height acquisition platform on a Tidal Turbine in the Falls of Warness, Orkney are analysed and discussed and the wider measurement campaign, of which they are part, is summarised. The acquisition platform array comprises three different types of Doppler sensor. The respective ability of each sensor to capture mean velocities, Turbulence Intensity (TI) and Integral Lengthscales are compared. Basic site characterisation in terms of the mean velocities show that Ebb and Flood tides exhibit different mean velocities and Depth Profiles. The three instruments show the Turbulence Intensity to range between 10% and 11% at 1m/s with significant increases in TI inversely with velocity (18% at 0.6m/s). The long range Continental sensor proves to be the only sensor with sufficient range to capture the streamwise Integral Lengthscale which is shown to correspond to approximately ¾ of the channel height (30-35m) at flow speeds above 1m/s for the flood tide data.

Keywords: Tidal-Energy, Turbulence, Doppler Sensors

1. Introduction

Tidal Energy Extraction is an emerging industry utilising devices which are deployed, by necessity, in harsh and complex conditions. The effects of turbulent flow on lifting surfaces is known, from the aeronautics and subsequently wind power industries, to significantly reduce both blade life and performance [1]. It is therefore vital for designers to understand and quantify the relationship between blade loading and turbulent flow. This begins with accurate measurement of the water velocities and to quantify the perturbations in the flow in a way that can be correlated with blade loadings. Turbulent flow is one in which the fluid velocity is irregular, varying in both time and direction over a range of scales [2].

ReDAPT (Reliable Data Acquisition Platform for Tidal) is a UK-based consortium commissioned and funded by the Energy Technology Institute, led by Rolls-Royce and including Plymouth Marine Laboratory, Tidal Generation Limited (TGL), Garrad Hassan, the University of Edinburgh (UoE), EDF Energy, E.ON, and the European Marine Energy Centre (EMEC). The project aims to install and test a 1MW tidal turbine at EMEC in Orkney, delivering detailed environmental and performance information not previously achieved at this scale in real sea conditions. A central aim of the University of Edinburgh's work in ReDAPT is to characterise the tidal flow surrounding the TGL 1MW turbine at EMEC's Tidal Test site in the Fall of Warness in the Orkney Isles. This data will be used to not only improve flow environment understanding but also to provide input parameters to a variety of numerical modeling activities being conducted by project partners.

In January 2012 the opportunity arose to test-run a limited instrument deployment on the 1MW turbine's predecessor, the TGL 500kW device, deployed at the same location. Seven acoustic Doppler instruments were installed on the turbine for a two month long campaign of flow data acquisition. The aim of this deployment was to commission the instrument package, highlight areas for instrumentation development and to capture the turbulence parameters deemed most likely to affect blade loadings.

2. Instrumentation and Experimental Setup

The site and Turbine location at the Fall of Warness are illustrated in figure 1. The turbine sits approximately 25m above the seabed in a section of channel with a mean depth of 43m. Figure 1 also highlights the location of standalone ADCP surveys captured by UoE and consortium partners.

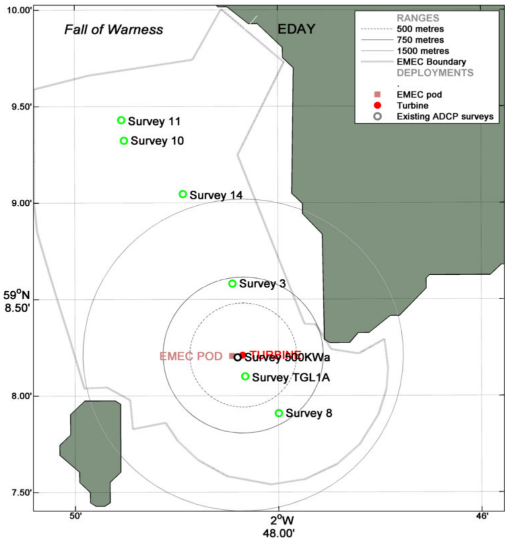

Figure 1: Location of the Test Site

A range of Doppler sensors were selected in order to allow the capture of different scales of motion at different sample rates and ranges. A newly available broadband Single Beam Doppler (SBD) was chosen for its flexibility and limited spatial averaging compared with a traditional multi-beam device, although it is limited to capture only along beam velocities. A long range single beam device, a Nortek Continental, was used to capture velocity inflow at a range of up to 100m and larger scales of motion. An "Acoustic Wave And Current" profiler (AWAC), which has a four beam arrangement, was used to resolve flow velocities above the turbine into three Cartesian vectors i.e., streamwise (u), transverse (v) and vertical (w). A summary of the devices can be viewed in table 1. This includes an RDI Workhorse ADCP which was deployed as a standalone device on the seabed to provide a separate reference velocity for future analysis work.

Device	SBD	AWAC	Cont-inental	ADCP
Range (m)	30	35	200	50
Sample Frequency (Hz)	2	1	1	2
Pulse Frequency (kHz)	1000	1000	190	600
Number of Beams	1	4	1	4

Table 1: Primary instrumentation features

The operation setup for the campaign is illustrated in figure 2. Measurements were taken with the turbine in a variety of orientations to the incident flow, but with the majority collected with the turbine reversed, i.e., the flow is incident to the rear of the turbine with the blades downstream.

3. Targeted Turbulence Metrics

There are several second order velocity metrics based on, u', the fluctuations about the mean, commonly used to quantify turbulence at a tidal site. The Turbulence

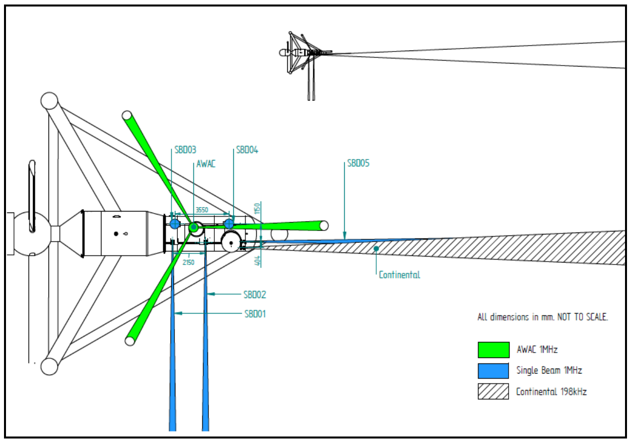

Figure 2: Sensor positions on TGL turbine.

Intensity, widely used in the wind industry and often used to characterise tidal sites, is defined in equation 1 and in equation 2 for single vector devices [3].

$$I = \frac{\sqrt{\langle u'^2 + v'^2 + w'^2 \rangle}}{\overline{u}} \tag{1}$$

$$I = \frac{\sqrt{\langle u'^2 \rangle}}{\overline{u}} \tag{2}$$

The Integral Lengthscale (equation 4) is a quantification of the largest structures in the flow [2] and is based on the autocorrelation function (equation 3).

$$R_{xx} = \frac{\langle u'(t,x) - u'(t,(x+r) \rangle}{\langle u'(t,x)^2 \rangle} \tag{3}$$

$$^{u}L_{xx} = \sum_{r=0}^{MaxLags} R_{xx} \tag{4}$$

Before any metrics are calculated, data is quality controlled to remove spurious points based on supplier recommendations for minimum returned beam signal level and noise correction [4-5]. The latter parameter leads to the corrected Turbulence Intensity, shown in figure 5, and is an important correction when using devices with instrument-specific noise characteristics [3].

$$I = \frac{\sqrt{\langle u'^2 + v'^2 + w'^2 \rangle - n^2}}{\overline{u}} \tag{5}$$

All turbulence metrics require an assumption of a period over which the flow can be assumed to be quasi-stationary. Throughout the early analysis contained in this report a preliminary assigned period of 10 minutes has been used. The importance of sensitivity analysis of the stationarity period and other Quality Control (QC) parameters is discussed in section 5.

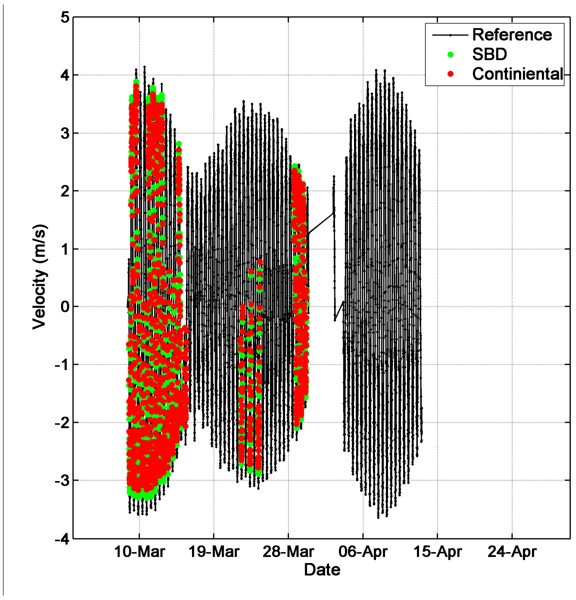

Figure 3: Reference and Single Beam Instrument Velocities highlighting a 20% capture rate (for this particular configuration) over March-April 2012

4. Observations

In order to characterise and discuss metrics discerned from the flow it is desirable to have a single point velocity for the site that these metrics can be referenced against. The velocity measured with the AWAC at a height of 12m above the turbine was chosen as this point was, from inspection, beyond the turbine's boundary layer and can give the true streamwise velocity for all turbine orientations.

Figure 3 shows the rear facing SBD and Continental velocities from the periods that the turbine was orientated reversed into the flow which covers approximately 20% of the period shown from early March to early April. The SBD and Continental track the reference velocity with a mean difference of 0.14m/s and 0.21m/s respectively. There is an under estimation (most visible at the extremes) which can be attributed to the turbine being orientated slightly off angle to the direction of maximum velocity. The bi-modal nature of the site can be observed with the Ebb tide (positive velocities) reaching speeds approximately 0.5m/s greater than those on Flood at spring tides.

The depth profiles for all streamwise velocities, averaged and binned in 0.5m/s increments at the reference velocity, are shown in Figures 4 and 5 for Flood and Ebb respectively. It is observed that the Ebb tide presents a greater reduction in velocity with depth when compared to the flood tides at high flow speeds. (0.5m/s difference in Ebb velocity compared to 0.2m/s in Flood velocity over 18m depth at the 3 to 3.5m/s bin). This is likely due to local bathymetrical effects. Above 20m the effect of the surface and waves can be observed.

The Turbulence Intensities against velocity from the three types of instrument mounted on the turbine are illustrated in figure 6. Figure 7 shows these values

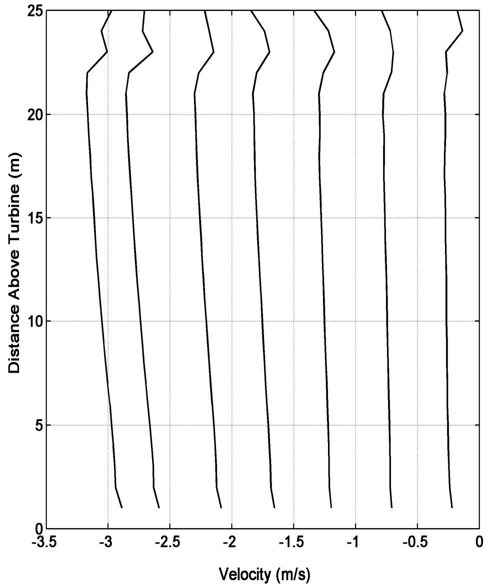

Figure 4: Flood Tide Depth Profile

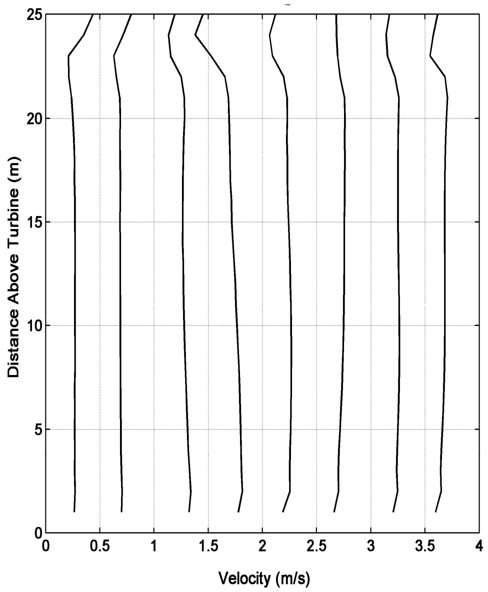

Figure 5: Ebb Tide Depth profile

curve fitted to a power law with the values given in table 2. The Broadband SBD exhibits a shallower gradient than the AWAC and Continental with the best R-squared fit. The curvature at low TI indicates a lower noise floor in the SBD compared with the narrowband devices.

The Turbulence Intensity is defined as being normalised by the mean velocity, thus its value increases with the inverse of velocity to very high values close to zero. Figure 8 shows the cumulative distribution function (CDF) of Turbulence Intensities for flow velocities greater than 1m/s. CDFs with cut-off velocities of 0.5m/s, 1m/s and 2m/s indicate a 95% probability of the TI being less than 20%, 13.5% and 9% respectively. Identifying the characteristic Turbulence Intensity for a tidal site is discussed in section 5.

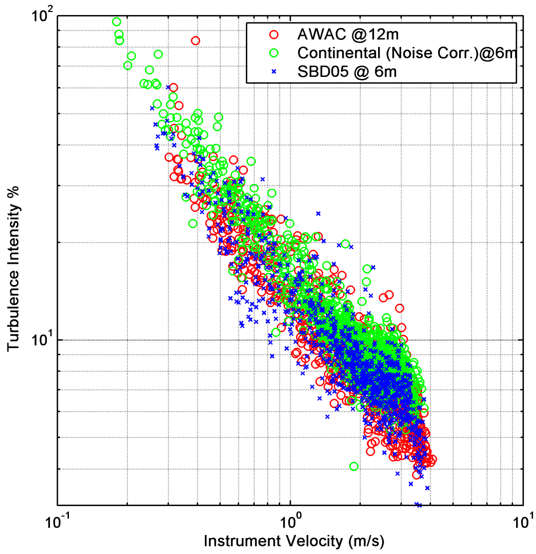

Figure 6: Turbulence Intensities

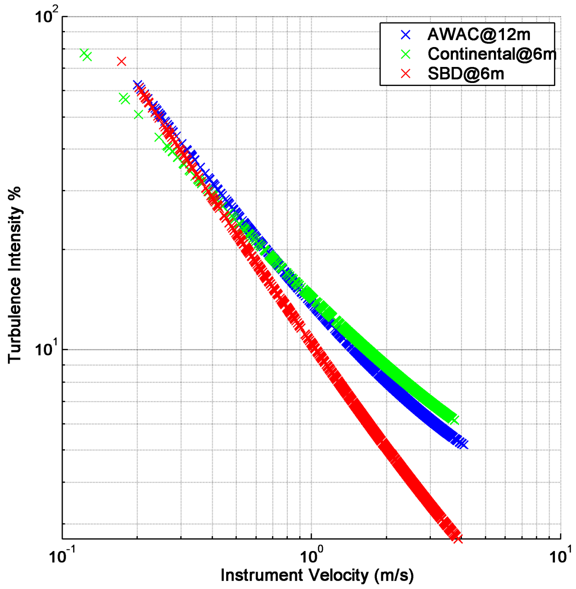

Figure 7: Turbulence Intensity Fit

Instrument	TI Equation	R-square
AWAC	TI = 11.5 * u $^{-1.0}$ +2.4	0.89
SBD	TI = 9.9 * u $^{-1.1}$ +3.6	0.91
Continental	TI = 12.0 * u $^{-0.9}$ +2.4	0.85

Table 2: Turbulence Intensity Fits

Figure 9 shows the streamwise Integral Lengthscale of the streamwise velocity reported by the Continental. For Ebb tide the mean lengthscale is 32.56m with a standard deviation of 1.7m for an established tide (I.E., one in which the flow is within 100 minutes either side of it's maximum value) and 17.20m for Flood tide with a standard deviation of 7.0m. The reason for this disparity in scales is unclear and further investigation is needed. The SBD's lack the necessary range to

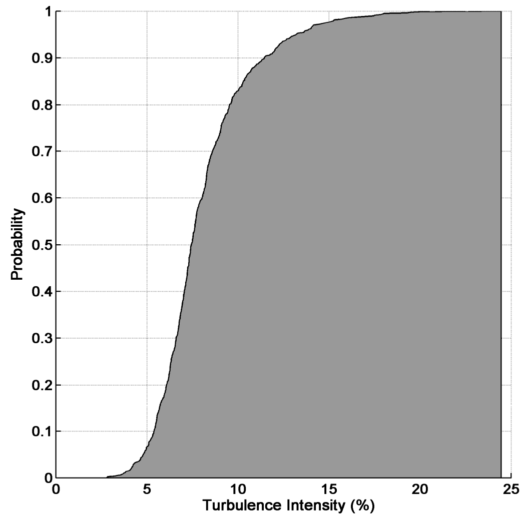

Figure 8: Empirical Cumulative Density Function of TI for flow velocities above 1m/s from SBD

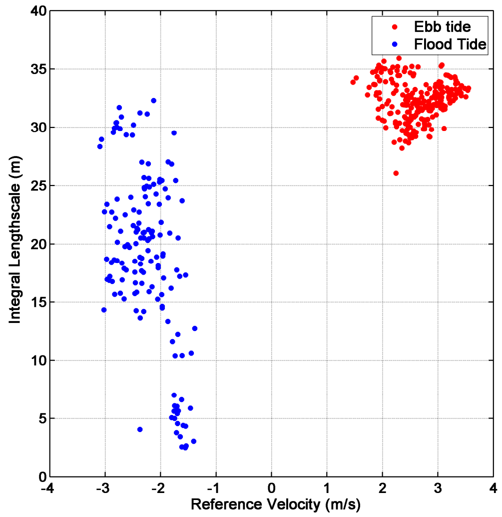

Figure 9: Integral Lengthscales from Continental

calculate lengthscales of this magnitude as a range of approximately 7 times that of the lengthscale being measured is required [6]. The SBD's effective range at the site was limited to about 20m and lengthscales were underestimated to a mean of 2.1m. However for smaller lengthscales the resolution afforded by the SBD's minimum bin size of 0.3m will be required as the minimum lengthscale that the continental can capture is 2m. Therefore, using the devices in tandem allows a greater range of lengthscales to be captured.

5. Discussion

The bi-modal nature of the site is not restricted to mean velocities but also includes depth profiles and turbulence metrics. This must be taken into consideration during analysis along with other temporal variations. It may be beneficial to subdivide tides into prescribed sub-stages which can track the variation over shorter periods.

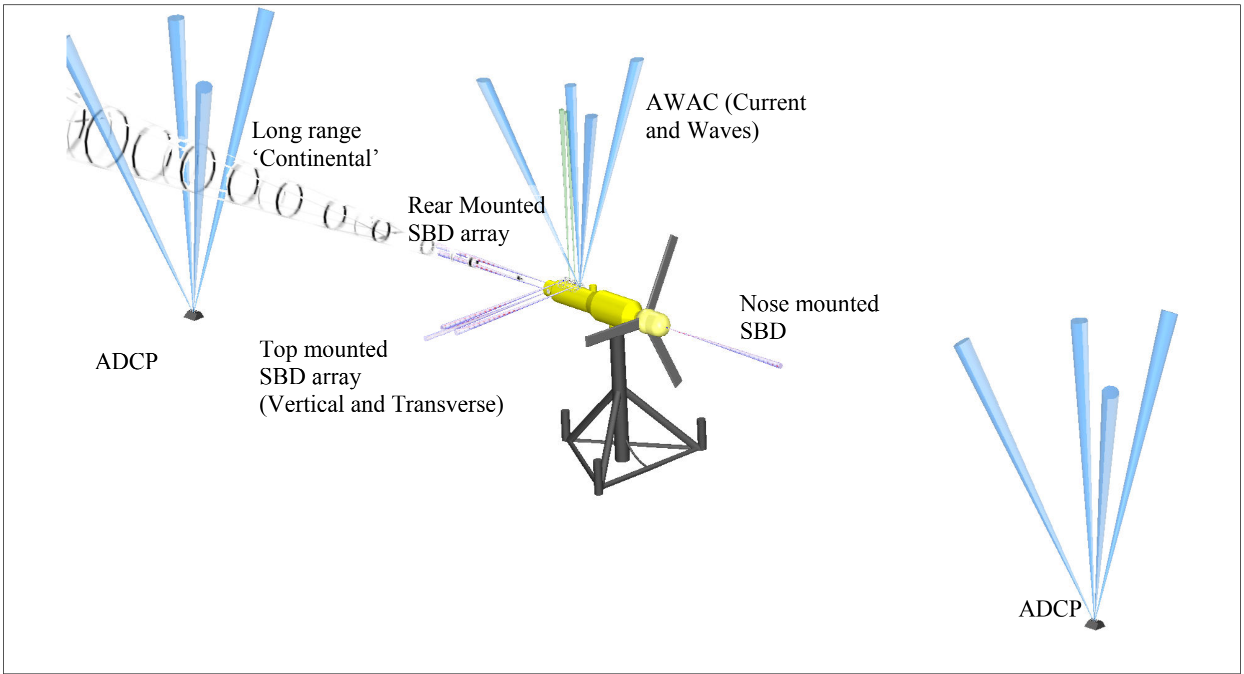

Figure 10: Outline of the instrumentation on and around the TGL 1MW Turbine

The Turbulence Intensity is often quoted as the indication of turbulent energy at tidal and wind sites, however, for tidal sites where the flow speed is constantly fluctuating about zero the value of TI which is representative of a site is difficult to define.

More work is required to both improve the measurement of Turbulence Intensity - via faster sampling rates, less spatial averaging and more accurate velocity measurements over a greater spatial domain - and importantly, to asses its validity within, and impact upon, tidal extraction systems due to the unsteady forces generated.

Coherent Turbulent Kinetic Energy and Dissipation Rate may prove to be a more appropriate set of metrics for Tidal sites. A key stage for tidal development will be the correlation of these turbulence metrics to statistically, if not directly, correlate with blade load data from the turbine blades.

All turbulence metrics are based on an assumption of stationarity over the period for which they are calculated. In reality the flow can only ever be quasi-stationary based on an acceptable drift of the statistics, such as mean and standard deviation.

6. Future Work

To the author's knowledge there has been no study on the sensitivity of turbulence metrics to a period of assumed stationarity, which would be of use for the industry and will be carried out as a part of this programme.

Quality Control has been shown to play an important role in acoustic instrument velocity capture [3], part of the future work will focus on the sensitivity of turbulence metrics to QC parameters and procedures.

A second, more comprehensive campaign on TGL's 1MW device is scheduled to commence in August 2012. This second campaign will comprise up to 20 Doppler sensors as well as vibration sensors to monitor instrument movement. A possible instrument configuration is illustrated in figure 10. Several novel array arrangements of the single beam devices will also be trialled with the goal of resolving the measured velocities into 3 Cartesian vectors with reduced spatial averaging compared to traditional diverging beam ADCPs. There will be supporting standalone ADCP deployments upstream and downstream from the turbine to characterise inflow and flow in the wake of the device.

ReDAPT partners are collecting strain data from a series of strain sensors mounted in the turbine blades. This gives the opportunity to statistically correlate the loadings on the blade to the occurrence of TI and Integral Lengthscales, as discussed in this paper, as well as other metrics including: Coherent Turbulent Kinetic Energy, Dissipation Rate and Power Spectra which, it is hoped, will shed light on the key fatigue load drivers.

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