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ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and one International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access are available to estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The initiative consists of five main Work Package focus areas: Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research, Training & Dissemination. The aim is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

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EXECUTIVE SUMMARY

One of the challenges the tidal power industry faces, is the requirement of cost effective, reliable but highly accurate acquisition of flow data. Different methods are required, applications range over different spatial and temporal scales. This report assembles in the first sections, theoretical background information on acoustic Doppler Velocimetry and RADAR measurements. The use of existing expertise in field tests of marine vehicles is discussed next, followed by a discussion of issues relating to recreating field conditions in laboratory environments. The last three sections present practical applications of various methods performed in field conditions.

While progress has been made over the last years, this overview highlights the challenges in full scale field measurements and knowledge gaps in the industry.
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1 INTRODUCTION

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The extraction of power from tidal flows is becoming increasingly popular, with an increasing number of companies developing tidal turbines. It is a well-known fact, that the power output is proportional to the cube of the flow velocity. Much less is known about the effect of turbulence on the devices and because a tidal stream is usually highly turbulent the description of these effects has raised interest among scientists.

Complications are due to the turbulence of the flow range from the correct evaluation of the representative inflow velocity, fatigue life and wake recovery.

Some methods to assess these flows have been used in other areas for years. Acoustic Doppler Velocimetres (ADV) and Acoustic Doppler Profilers (ADP) have been used to measure point samples of velocity at high frequency or velocity profiles averaged over several beams respectively.

However the application to specific problems in the tidal industry is often not straightforward. Besides the common issue of sufficient time and spatial resolution, accessibility of the area of interest can be a challenge around tidal devices.

Post processing requirements for these measurements might also often be different from applications in other areas.

A different approach to measure high frequency turbulence is implemented in the MicroRider turbulence profiler for the smallest scales, while large scale current measurements can be performed using RADAR technology.

This report presents a collection of the state of the art of different technologies, like a review of ADV and RADAR technology (Chapters 2 and 3). Chapter 4 reviews existing guidelines for full scale field testing of marine vehicles and tries to find possible applications for field testing of tidal turbines. Chapter 5 then investigates consequences for small scale laboratory testing from refined full scale flow assessments. The application of a turbulence profiler in the vicinity of a tidal turbine is discussed in chapter 6. Chapter 0 presents attempts to apply standard ADV and ADP technology to assess the wake of a full scale tidal turbine.
2 REVIEW OF ADV TECHNOLOGY

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2.1 INTRODUCTION

This report presents a contribution to the study on "New instrumentation and field measuring technology" (Task 4.2.1) of WP4 of the Marinet project devoted to "research to innovate and improve Infrastructures, technologies and techniques." Elements introduced in this document are mostly based on state of the art references on methodologies for assessment of the variability of the flow in the highly energetic sites usually considered for tidal power extraction. The focus here is mostly on methods for assessment by mean of acoustic devices such as ADCP or ADV of turbulent structures at scales corresponding to the main dimensions and size of the turbines or conversion devices to be placed in the water column.

2.2 REQUIREMENTS

Tidal turbines are to be deployed on sites located in intermediate waters (~30 m to ~50 m) were strong tidal currents occur having velocities up to ~5 m/s and were operational current velocities should be at least ~2 m/s. In such locations, the flow is usually not laminar and with a high variability, often assimilated to turbulence. Reasons for such variability, in addition to the flow characteristics are mainly related to:

- uneven bathymetry
- seabed surface roughness
- wave kinematics and wave-current interactions

Such variability is relatively not well-known, especially at the metric and decametric scales corresponding to the main dimensions of the tidal turbines susceptible to alter the production and efficiency of the machines as well as inducing additional fatigue loading.

Engineering and design of tidal turbines requires an accurate knowledge of loading on the structures, forces, bending moments on each element of the structure, basement, hub, rotor and blades (Mile 2010; McCann 2008).

2.3 PARAMETERS TO BE IDENTIFIED

$U$ is the local velocity evaluated from the mean value of the components of the velocity, $U_x$, $U_y$, $U_z$.

$$U = \sqrt{U_x^2 + U_y^2 + U_z^2}$$

In the case of turbulent flow, this local velocity is usually decomposed in two components, a mean velocity $\overline{U}$ and a fluctuating component $u'$:

$$U = \overline{U} + u'$$

Turbulence intensity is generally defined as the ratio of the standard deviation of the fluctuating velocity component over the mean velocity:

$$I = 100 \times \frac{u'}{\overline{U}}$$
The turbulent Kinetic Energy $k$ is given by:

$$k = \int_{0}^{\infty} E(k)dk$$

Where $E$ is the energy spectral density and $k$ is defined by:

$$k = \frac{1}{2} \sqrt{\overline{u_x'^2} + \overline{u_y'^2} + \overline{u_z'^2}}$$

The components of the Reynolds stress are defined as:

$$
\begin{align*}
\overline{u_x'u_y'} \\
\overline{u_x'u_z'} \\
\overline{u_y'u_z'} \\
\end{align*}
$$

They allow identification of raising coherent turbulent structures in the case of homogeneous mixed flows.

The Coherent Turbulent Kinetic Energy CTKE is defined by:

$$CTKE = \frac{1}{2} \sqrt{(\overline{u_x'u_y'})^2 + (\overline{u_x'u_z'})^2 + (\overline{u_y'u_z'})^2}$$

It is of interest for identification of the Reynolds stress peaks.

Anisotropy amplitude $A$ is defined by:

$$A = \frac{1}{4} \left( 2 \left( \overline{u_x'^2} + \overline{u_y'^2} + \overline{u_z'^2} \right) + \overline{u_x'^2} + \overline{u_y'^2} + \overline{u_z'^2} \right)$$

This scalar is independent of the referential and has the same dimension as an energy. Its value is zero in the case of an uncorrelated isotropic turbulence.

Frequency spectra of the turbulent component are given by:

$$
\begin{align*}
\langle u_x'^2 \rangle &= \int S_{ux'u_x}(f) df \\
\langle u_y'^2 \rangle &= \int S_{uy'u_y}(f) df \\
\langle u_z'^2 \rangle &= \int S_{uz'u_z}(f) df \\
\end{align*}
$$

Spectral analysis allow identification of the time scales associated with the turbulent structures from which turbulence length scales can also be derived.

Turbulent structures length scales $L_\tau$ are characterized by the parameter:

$$L_\tau = \frac{k_\tau}{\epsilon}$$

Where $\epsilon$ is the turbulence dissipation rate:
\[ \epsilon = \nu \int_0^\infty 2Kk^2 E(Kk) \, dk \]

and \( \nu \) is the fluid viscosity.

Usual parameters for turbulence characterization are summarized in the table hereafter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
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<td>Mean velocity</td>
<td>( \overline{U} = \sqrt{U_x^2 + U_y^2 + U_z^2} )</td>
</tr>
<tr>
<td>Turbulent intensity</td>
<td>( I = \frac{u'}{U} )</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>( k = \int_0^\infty E(k) , dk = \frac{1}{2} \sqrt{\overline{u_x^2} + \overline{u_y^2} + \overline{u_z^2}} )</td>
</tr>
<tr>
<td>Reynolds stress</td>
<td>[ \begin{bmatrix} \overline{u_x'u_y'} &amp; \overline{u_x'u_z'} &amp; \overline{u_y'u_z'} \end{bmatrix} ]</td>
</tr>
<tr>
<td>Coherent Turbulent Kinetic Energy</td>
<td>( CTKE = \frac{1}{2} \sqrt{(u_x'u_y')^2 + (u_x'u_z')^2 + (u_y'u_z')^2} )</td>
</tr>
<tr>
<td>Anisotropy Amplitude</td>
<td>( A = \sqrt{\frac{1}{4} \left( 2 \left[ \overline{u_x'u_y'^2} + \overline{u_x'u_z'^2} + \overline{u_y'u_z'^2} \right] + \overline{u_x'^2} + \overline{u_y'^2} + \overline{u_z'^2} \right)} )</td>
</tr>
</tbody>
</table>
| Turbulent spectra                   | \[ \begin{align*} 
\langle u_x'^2 \rangle &= \int S_{u_x'u_x'}(f) \, df \\
\langle u_y'^2 \rangle &= \int S_{u_y'u_y'}(f) \, df \\
\langle u_z'^2 \rangle &= \int S_{u_z'u_z'}(f) \, df 
\end{align*} \] |
| Turbulence scale lengths            | \( L_T = \frac{k^2}{\epsilon} \)                                       |
| Turbulence dissipation rate         | \( \epsilon = \nu \int_0^\infty 2k^2 E(Kk) \, dk \)                      |

**Table 1: Turbulence parameters**
2.4 Methodologies for Flow Measurement

Some basic principles and methods identified in the recent literature for assessment of the turbulence in energetic flows and in relation with loading on tidal turbines are provided hereafter. The presented methods are related to measurements of the flow velocity and identification of its variability by mean of acoustic devices such as Acoustic Doppler Current Profilers (ADCP) or Acoustic Doppler Velocimeter (ADV).

Even such devices are not, in their principle well adapted to the assessment of the high frequency variability of the flow, many studies have been conducted over the recent years with the objective of improving the quality of assessment of turbulent structures and eddies.

Among the identified difficulties the assessment and filtering of the Doppler noise as well as the characterization of the wave kinematics are affecting the analysis of the turbulent structures in the inertial range, which is of interest for the design of current turbines.

Additionally, it can be noted that the existing methods are based on assumptions having a limited range of validity and which cannot always be verified.

2.4.1 Variance method

The variance method (Stacey, 1999; Lu & Lueck 1999a, b; Dewey, 2007) is the most widely used method to characterize flow variability through the evaluation of metrics such as Reynolds Stress or turbulent kinetic energy density.

We consider here the use of a four beams ADCP, place on the seabed. Beams are positioned in two orthogonal plans, each having an angle \( \theta \) with the vertical. The beam velocity \( b_i \) is associated with each of the beams at the elevation \( z \) above the sensor. Beams 1 and 2 (resp. 3 and 4) are positioned in the same plan.

Horizontal and vertical components of the velocities associated with each beam in the terrestrial referential, \( u, v, w \), are related to the beam velocities by mean of the relations:

\[
\begin{align*}
b_1 &= -u_1 \sin \theta + \varphi_3 \cos \theta - w_1 \cos \theta + \varphi_2 \cos \theta \\
b_2 &= u_2 \sin \theta - w_2 \cos \theta + \varphi_2 \cos \theta \\
b_3 &= -v_3 \sin \theta - w_3 \cos \theta - u_3 \varphi_3 \cos \theta \\
b_4 &= v_4 \sin \theta + \varphi_2 \cos \theta - w_4 \cos \theta - u_4 \varphi_3 \cos \theta 
\end{align*}
\]

Reduced to:

\[
\begin{align*}
b_1 &= -u_1 \sin \theta - w_1 \cos \theta \\
b_2 &= u_2 \sin \theta - w_2 \cos \theta \\
b_3 &= -v_3 \sin \theta - w_3 \cos \theta \\
b_4 &= v_4 \sin \theta - w_4 \cos \theta 
\end{align*}
\]

when the ADCP is fixed mounted on the seabed with no tilt and the pitch angle \( \varphi_2 \) and roll angle \( \varphi_3 \) are zero (\( \varphi_1 \) corresponds to the yaw angle around the vertical axis).

Velocities in the terrestrial referential are then obtained differentiating the beam velocities in each vertical plans:

\[
\begin{align*}
u &= \frac{b_2 - b_1}{2 \sin \theta} - \varphi_3 \frac{b_2 + b_1}{2 \cos \theta} \\
v &= \frac{b_4 - b_3}{2 \sin \theta} - \varphi_2 \frac{b_4 + b_3}{2 \cos \theta} \\
w &= -\frac{b_1 + b_2 + b_3 + b_4}{4 \cos \theta} - \varphi_3 \frac{b_2 - b_1}{2 \sin \theta} + \varphi_2 \frac{b_4 - b_3}{2 \sin \theta}
\end{align*}
\]

In order for these expressions to be valid and for the velocity components, \( u, v, w \) to correspond to the true velocity, the velocity components at each beam must be equal. In other words, the velocity field must be homogeneous in the...
horizontal plane over the length corresponding to the separation distance between two opposing beams. This condition is actually never exactly satisfied, because of the presence in the flow of turbulent structures having the size or smaller than the distance of separation between beams.

Hence, one usually assumes that the statistical properties of the flow are homogeneous in the horizontal plane. In detail, the mean tridimensional flow characterized by the mean components \((\bar{u}, \bar{v}, \bar{w})\) is considered homogeneous in the horizontal plane over the separation distance between the beams, whilst the mean of the velocity fluctuations is zero.

Such horizontal homogeneity assumption requires taking into account, in order to obtaining a reasonably satisfying assessment of the mean flow, a sufficient duration \(\tau \gg L/U\) where \(U\) is the mean flow velocity and \(L\) is the distance between two beams.

A reference criterion can be defined as the ratio of the mean horizontal scale over the separation distance: \(M = \frac{\bar{u}\tau}{L}\). A value \(M=50\) is considered (Lu & Lueck, 1999) in agreement with the assumption of statistical horizontal homogeneity. (For instance considering a measurement at 20 m above the ADCP and beams at an angle of 20° with the vertical, 1m/s flow velocity would require an averaging time of about 12 min.)

**Figure 1:** Beam separation distance as a function of elevation in the water column

Considering a turbulent flow, beam velocities can be decomposed in a mean component \(\bar{b}_i\) and a fluctuating component, \(b'_i\), as the velocity components in the terrestrial referential:

\[
\begin{align*}
    u &= \bar{u} + u' \\
    v &= \bar{v} + v' \\
    w &= \bar{w} + w'
\end{align*}
\]

Reynolds stresses can be derived taking into account the variance of the turbulent component of the beam velocities:
\[ -\overline{u'w'} = \frac{b_1^2 - b_2^2}{2\sin2\theta} + \varphi_3\left(\overline{u'^2} - \overline{w'^2}\right) - \varphi_2\overline{u'v'} \]

\[ -\overline{v'w'} = \frac{b_4^2 - b_3^2}{2\sin2\theta} + \varphi_2\left(\overline{v'^2} - \overline{w'^2}\right) + \varphi_3\overline{u'v'} \]

In this expression, the values: \( \overline{u'^2} - \overline{w'^2} \), \( \overline{v'^2} - \overline{w'^2} \), and \( \overline{u'v'} \) are not determined and neglecting. They will necessarily induce a bias in the estimate of the Reynolds stress. This bias is proportional to the amplitude of the tilt angles and can be considered limited for tilt values lower than 2°. Additionally, if the flow can be considered isotropic, the difference components \( \overline{u'^2} - \overline{w'^2} \) and \( \overline{v'^2} - \overline{w'^2} \) will be small.

Furthermore, assessment of the Reynolds stresses requires that pitch, roll and yaw remain invariant in time. As a consequence, the ADCP should be fixed on a rigid frame.

In addition to the Reynolds stresses, it is also possible to assess the turbulent kinetic energy density from the variance of the fluctuating components of the beam velocities:

\[
\frac{q^2}{2} = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)
\]

Evaluating the quantity:

\[
S = \frac{1}{4\sin^2\theta}\left(b_1^2 + b_2^2 + b_3^2 + b_4^2\right) - (\varphi_3\overline{u'w'} - \varphi_2\overline{v'w'})\left(\frac{2}{\tan^2\theta} - 1\right)
\]

Which is:

\[
S = \frac{1}{1 + \alpha}\left(1 + \frac{2\alpha}{\tan^2\theta}\right)\frac{q^2}{2}
\]

with

\[
\alpha = \frac{\overline{w'^2}}{\overline{u'^2} + \overline{v'^2}}
\]

where \( \alpha \) characterizes the turbulence anisotropy (\( \alpha = 0.5 \) for an isotropic turbulence and \( \alpha = 0 \) for highly anisotropic conditions).

Assessment of this anisotropy coefficient requires the use of a 5 beams ADCP (Dewey, 2007) with a vertical component allowing an accurate measurement of the vertical component of the vertical velocity and its variance.

### 2.4.2 Taylor’s « frozen field » assumption

Taylor’s « frozen field » assumption (Townsend, 1948) is used to assess the spectral structure of a turbulent velocity field from a local measurement of the time fluctuations of the velocity at a fixed point.

“If the velocity of the air stream which carries the turbulent eddies is very much greater than the turbulence velocity, one may assume that the sequence of changes in \( u \) at a fixed point are simply due to the passage of an unchanging pattern of turbulent motion over the point.”

This assumption requires that the mean flow at the duration of the transport of the turbulent structures at the location of the sensor is very short regarding of the turbulence evolution time scale (Belmonte, 1999).

In practice should be: \( \overline{u'^2} \ll \overline{u'^2} \).
Considering space evolution of the flow:

\[ u(x, t) = u(x + \Delta x, t + \tau_0) \]

with \( \tau_0 = \frac{\Delta x}{u_0} \), \( u_0 \) the mean flow velocity and \( \Delta x \) the distance between the two considered reference locations in the direction of the main mean flow.

The main interest of this assumption is to link, for any scalar value, its time derivative assessed at a unique measurement location to its space derivative:

\[ \frac{d\varphi}{dx} = u_0 \frac{d\varphi}{dt} \]

Taylor’s assumption is potentially valid only in the cases when turbulence intensity, shear rates and viscous damping are low in the range of the considered length scales (typically the beam separation distance for an ADCP).

### 2.4.3 Doppler Noise

Doppler noise is induced by the intrinsic limitations related to the assessment of the Doppler shift from a signal having a limited duration (Durgesh, 2014). This random noise affecting velocity measurement has various causes:

- Duration of the acoustic signal (ping),
- Signal frequency and amplitude,
- Bins size,
- Signal range,
- Flow quality (velocity and turbulence intensity)
- ...

ADCP Doppler noise is usually higher than Doppler noise observed with ADVs.

### 2.4.4 Doppler noise reduction

Parameterization of an ADCP can be optimized to minimize the Doppler noise (Thomson, 2012). When the random error corresponding to the Doppler noise is decorrelated from one ping to the next, evaluation of an ensemble average over \( N \) successive measurements will reduce this error as \( \sqrt{N} \). However, when assessing turbulence, computing ensemble averages over large numbers of measurements will affect the evaluation of the variance of the velocity. As a consequence, it is generally recommended to record the high frequency signal and then to remove the Doppler noise by mean of statistical methods taking the variance of the velocity into account.

The sampling frequency \( f_s \) can be optimized considering that the turbulent structures advected by the mean flow \( \bar{u} \) having a length scale of the order of the beams separation distance \( \Delta b \). Hence, considering Taylor’s assumption:

\[ f_s = \frac{2\bar{u}}{\Delta b}. \]

Another parameter to be taken into account for reducing Doppler noise is the duration of the pulses (ping). Longer pulses induce lower noise than shorter pulses which on the other hand allow a smaller bin size. As a consequence, it is recommended to choose settings to get the largest acceptable bin size. For instance, the optimal bin size for considering should correspond to the minimum resolution, allowing assessment of the vertical shear of the mean flow \( \frac{d\bar{u}}{dz} \).
In any case, sampling parameterization should be set that Doppler noise will be largely lower than the expected turbulent fluctuations, based on an a priori estimate of the mean flow velocity and considering a reference turbulence intensity of about 10% (Thomson, 2010).

2.4.5 Doppler noise filtering

Even though Doppler noise can be reduced using optimal settings of the ADCP, it will still exist. Hence various filtering methods are proposed as for instance the Noise Auto-Correlation (Durgesh, 2014).

Assuming the Doppler noise is a white noise, the measured velocity is considered as the superimposition of the true velocity and a white noise:

\[ u(t) = u_t(t) + w_n(t) \]

Hence, the autocorrelation is given by

\[ R_{uu}(\tau) = E[u_t(t) u_t(t + \tau)] = R_{uuu}(\tau) + R_{uw}(\tau) + R_{ww}(\tau) \]

In this expression, the cross-correlations \( R_{uuw}(\tau) \) and \( R_{wwu}(\tau) \) will cancel for long time series. As a consequence, the autocorrelation of the signal can be approximated as the summation of the two auto-correlations:

\[ R_{uu}(\tau) = R_{uuu}(\tau) + R_{ww}(\tau) \]

Since the auto-correlation of white noise is a delta function the autocorrelation of a noisy signal will exhibit a peak at zero time-lag. Namely

\[ R_{ww}(\tau) = B \text{ if } \tau = 0 \\
0 \text{ if } \tau \neq 0 \]

Finally the autocorrelation of the true velocity can be derived from its corrected auto-correlation function:

\[ R_{uuu}(\tau) = R_{uu}(\tau) - R_{ww}(\tau) \]

Other methods such as Singular Value Decomposition or Proper Orthogonal Decomposition (POD) can also be used to filter the Doppler noise.

The POD method allows identification of the dominant structures in the turbulent flow. Considering the modes \( M_p \) associated with these energetic coherent structures, the velocity is recomposed in the form:

\[ u(t) = \sum_{p=1}^{N} a_p^u M_p \]
The less energetic non coherent structures associated with the noise are filtered summing only the energetic components in the recomposition.

### 2.5 Wave kinematics

A major difficulty in the assessment of turbulence is coupling with the wave kinematics. As energy associated with waves mostly lies in the inertial range corresponding to the coherent turbulent structures. Various methods have been proposed in order to filter the wave components in the ADCP signals.

#### 2.5.1 Wave kinematics identification and filtering

The coherence method (Hoitink et al. 2007) is based on the assumption that the turbulent structures are not coherent along the water column contrarily to the kinematic components (orbital velocities) associated with waves. As a consequence, if the velocity is decomposed in flow velocity $u_t(t)$ and wave velocity $u_w(t)$ components

$$u(t) = u_t(t) + u_w(t)$$

The contribution of waves to the velocity spectrum $S_u$ can be identified introducing the coherence $\gamma_{u(t)}$ between the velocity assessed at a given elevation and the velocity averaged over the water depth $\langle u \rangle$:

$$S_{u_w} = \gamma_{u(t)}^2 S_u$$

It should be noted that the assumption on coherence does not stand in all situations.

The variance fit method (Whipple, 2006) does not rely on this assumption. It is based on the analysis of the differences of the beam velocities measured at two elevations $a$ and $b$ along two beams in the same vertical plane:

$$\Delta u_3 \equiv u_{3b} - \beta u_{3a} = u_{3b}^t - \beta u_{3a}^t + \tilde{u}_{3b} - \beta \tilde{u}_{3a}$$

$$\Delta u_4 \equiv u_{4b} - \beta u_{4a} = u_{4b}^t - \beta u_{4a}^t + \tilde{u}_{4b} - \beta \tilde{u}_{4a}$$

where $\beta$ characterizes wave kinematics attenuation with depth and is identified so that the term $\tilde{u}_{3b} - \beta \tilde{u}_{3a}$ cancels (using wave linear theory).

Hence the Reynolds stress averaged over the distance between points $a$ and $b$ can be derived from the term:

$$RS_{ab} = \frac{\Delta u_3^2 - \Delta u_4^2}{4 \sin \theta \cos \theta (1 + \beta^2)}$$

It should be noted that the distance between locations $a$ and $b$ should be large enough for the turbulence to be decorrelated but small enough for the Reynolds stress not to vary too much between $a$ and $b$ (typically $\sim 1m$).

Such method is based on three major assumptions:

- Wave orbital phase should be constant along the water column,
- Kinematics decay with depth is based on the linear theory
- Kinematics decay should be similar for the 2 opposing beams.

Similar methods, that do not require such restrictive assumptions, are being developed (Rosman, 2008).
2.6 REFERENCES


3 RADAR USE IN TIDAL MEASUREMENTS

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3.1 INTRODUCTION

Traditionally the output of marine X-band radar has been used for detecting hazards and assisting navigation. By implementing the Ocean Waves Gbmh Wave and Surface Current Monitoring System (WaMoS®II) software to the marine radar output it can be used to make non-intrusive measurements of the sea state. Sea state parameters that can be measured include wave height, wave direction and wave period and surface velocity. The WaMoS®II system can be installed on fixed or moving platforms, on board all types of vessel and can be fixed on coastal sites. The European Marine Energy Centre (EMEC) has installed two OceanWaves Gbmh WaMoS®II Wave Monitoring systems, one at each test site in the coastal configuration. The first unit installed at the substation on the isle of Eday [059°09.969N; 002°48.465W] to monitor the Fall of Warness tidal test site (funded by the ReDAPT project). The system on Eday consists of dedicated PC+PCI Interface card and is fed with data from a Kelvin Hughes MANTA 1700 marine radar system provided by the National Oceanography Centre (see Figure 1). The second is installed at the Billia Croo substation to monitor the wave test site, coordinates [058°58.322N; 003°21.033W] which consists of a dedicated PC+PCI Interface card and is fed from Furuno FAR-21x7-BB series radar. The marine radars operate continuously to provide site-wide measurements based on to back scatter of microwaves from the sea surface as well as provide supporting information for marine operations carried out on the sites.

Figure 1. Marine X band radar system installed at EMEC substation Eday.

These marine radar systems are a combination of contemporary analysis techniques with long-established measurement hardware. It is being applied at present to both of EMEC’s marine test sites and is consistently undergoing calibration in order to fine tune the set-up. This is to ensure that the output is representative of the conditions on the test sites and to provide feedback on the effectiveness of such radar systems in the field of tidal measurements. This section of the report aims to disclose the findings of the use of the WaMoS®II system so far including potential future benefits. The output data provides a supplementary data stream that can be used for cross-correlation with other measurement techniques. It also provides a site-wide spatial and temporal measurement tool increasing the understanding of the variability of tidal conditions experienced across both the wave and tidal test site.

3.2 TECHNOLOGY

Under various conditions, signatures of the sea surface are visible in the near range of nautical radar images (< 3 NM) and are commonly known as sea clutter. These signatures are generally undesirable for navigational purposes...
and tend to be filtered by standard algorithms. The sea clutter is generated by the backscatter of the transmitted electromagnetic waves from short sea surface ripples; generally in the order of cm. Longer waves modulate the sea clutter signals and therefore become visible in the radar images.

Standard nautical X-band radar system that use radio waves between 8 and 12 GHz, which allows scanning of the sea surface with high temporal and spatial resolution. With each antenna revolution of the radar; the sea surface is scanned by electromagnetic waves. The received backscatter intensity from the sea surface is transferred via an isolated buffer to the analogue to digital (AD) converter in a PC. On the WaMoS®II PC the data is stored and analysis is carried out. Sea surface and sea state information can be captured in near-real time. The X-band radar signal is reflected by Bragg scattering from surface capillary roughness and resulting intensities can map the gravity of the waves on the ocean surface. FFT analysis provides wavelength/period pairs of estimates. When these pairs are fitted at multiple frequencies to the dispersion relationship \((\sigma + k)^2 = g \cdot k \cdot \tanh(k \cdot h)\) current speed in the water can be estimated. In addition to the standard WaMoS®II installation EMEC have also purchased the High Resolution Current (HRC) software package. This has the potential for retrieval of more detailed temporal and spatial current measurements from the X-band radar images on a fine grid of 150m x 150m at Billia Croo and a coarser 600m x 600m grid at the Fall of Warness. In shallow water (< 50m) local depth can be derived from the ocean surface wave characteristics. The main parameters that can be derived from the HRC software are detailed in Table 2. Sea surface currents (speed and direction) are derived from the unambiguous wave spectrum in near real time using Doppler shift theory to determine influence of the tide on the waves being measured (Hessner, 2009).

<table>
<thead>
<tr>
<th>HRC Data Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth, accumulated</td>
<td>(D_a) (m)</td>
</tr>
<tr>
<td>Water Depth, instantaneous</td>
<td>(D_i) (m)</td>
</tr>
<tr>
<td>Surface Current Speed</td>
<td>(U) (m/s)</td>
</tr>
<tr>
<td>Surface Current Direction</td>
<td>(\Theta_u) (°)</td>
</tr>
<tr>
<td>Encounter Current Speed(^1)</td>
<td>(U) (m/s)</td>
</tr>
<tr>
<td>Encounter Current Direction(^2)</td>
<td>(\Theta_u) (°)</td>
</tr>
<tr>
<td>Significant Wave Height</td>
<td>(H_s) (m)</td>
</tr>
<tr>
<td>Peak Wave Period</td>
<td>(T_p) (s)</td>
</tr>
<tr>
<td>Peak Wave Direction</td>
<td>(\Theta_p) (°)</td>
</tr>
<tr>
<td>Peak Wave Length</td>
<td>(\lambda_p) (m)</td>
</tr>
</tbody>
</table>

Table 2. Summary of main parameters derived from WaMoS®II HRC.

For best performance the WaMoS®II software applies an internal quality control system. The two thresholds that contribute to this are current speed and water depth. The expected extreme value indicators should be programmed to ensure that unrealistic parameters are neglected when analysis is carried out by the software. For the scope of this report the parameters that will be examined are the surface current speed and the surface current direction from the standard WaMoS®II software analysis. As the HRC software is still undergoing commissioning at both EMEC test sites the outputs from this data feed will not be explored in detail.

### 3.3 Application

Both WaMoS®II systems operating at EMEC are, at present, in the development stage. As the software has not often been applied in the unique circumstance of full scale marine energy test centre calibration is on-going to improve the quality of the data outcomes. Despite this the data from the WaMoS®II systems has been used to supplement other measurements for a number of projects. Data acquisition campaigns and in house analysis techniques are enduring to establish the effectiveness of the technology and to assist with the improvement of the quality of the data. Calibration has up until now been carried out by software developers Ocean. It is carried out by comparing the radar output with another form of measurement such as a buoy or ADCP and applying the resultant calibration coefficient to the operative calibration file. Calibration has been applied to the radar system at the Fall of Warness.

\(^1\) Optional, only for measurements from moving ships
\(^2\) These values are guideline values and depend on the radar and measurement settings.
which has greatly improved the surface current and direction measurements as a result. EMEC is looking to develop an in-house calibration routine to the Billia Croo radar system in the near future.

EMEC has selected a number of Cartesian measurement boxes at each radar site that provide spatial measurements within the selected area. The locations of the three boxes at the Fall of Warness test site can be seen in [Error! Reference source not found.] below. Each box is approximately 600m x 600m and data from within the box represents a spatially averaged value. The HRC software will be able to provide the measurements as discussed in Table 2 above for a number of 600m$^2$ grid boxes that populate the majority of the area within the orange radar boundary in Figure 3 below.

Figure 3. Coverage of Eday radar including locations of the Cartesian measurement boxes.

There is one Cartesian measurement box at the Billia Croo test site that is approximately 1200m x 600m in size as see in Figure 4 below.
An advantage of the WaMoS®II software is that it can provide temporal and spatial variability in surface currents across the EMEC test sites where other equipment, such as Acoustic Doppler Current Profilers (ADCP) only provide a spot measurement. This can may be more practical than gathering data using an ADCP as these are normally located on the seabed and require the data to a shore based station where radio communications are not possible. As an ADCP is a single point measurement device a network of devices would need to be deployed in order to provide good spatial coverage which would require multiple units and the associated costs of marine works for deployment. A marine radar can be installed without expensive marine operations and the coverage allows tidal current and direction to be measured over a greater area of sea. EMEC has already provided the near-real time data feed from the WaMoS®II to a number of developers currently on site. From the Surface Current velocity and direction analysis can be done to provide further outputs such as constituent mapping, spatial current maps of the areas of interest, detection of shear zones, tidal phase analysis, tidal harmonic analysis and long range tidal predictions. Quality control of the radar data is important as all parameters are derived from a return in signal and errors are propagated through the analysis from the original radar images. Data can be quality controlled by means of analysing the signal to noise ration and determining an adequate threshold for data rejection.

### 3.4 Outcomes

#### 3.4.1 High Resolution Currents

As the WaMoS®II can be used to derive spatial variability in tidal currents EMEC will be able to derived surface current readings over a 5km at both the Fall of Warness tidal site and the Billia Croo wave test site using the HRC data measured by the radar. Using MATLAB the HRC files can be interpreted and converted into a visual representation of the tidal conditions at any given measurement point. Code derived in house in addition to code provided by Dr. Paul Bell for the National Oceanographic Centre have been used to produce the analyses below. Figure 5 shows the HRC output at the Fall of Warness test site. Flow during the flood tide comes from a south easterly direction and then retreating on the ebb tide in a north westerly direction. Flows in the region of 4.5 m/s can be seen in both the flood and ebb tides. This is consistent with measurements from ADCP surveys carried out in the same location.
3.4.2 Cartesian box analysis

Data from Cartesian box 3 at the Fall of Warness is shown below. Figure 6 shows the uncalibrated output from the radar compared with the output for the same location from the DHI hydrodynamic model from January 2012. The Hydrodynamic model has been fine tuned for the EMEC test sites. As can be seen in Figure 7 below the calibrated data from the same period in 2015. While the box has moved location between 2012 and 2015 the calibrated data show a closer comparison between the two datasets which indicates the value of a robust calibration being applied to the WaMoS®II system.
3.4.3 Polar files

Raw data from the radar are collected in Polar files. Figure 8 represents one rotation of the radar antenna and shows the sea clutter collected in this rotation which has been transformed to Cartesian coordinates. Wave crests can be seen in the image and show up white in the image. Polar images provide the basis of the current analysis as described in the sections above. When the waves conditions are not favourable, for example if the wave heights are too low or there is a lot of background noise from heavy rain, the polar files may be too poor to carry out the necessary transformations.
3.5 DISCUSSION

Although the WaMoS®II technology is still in the development stage here at EMEC it has already shown potential for both present and future applications. The data feed being streamed to developers upon request and has been used to supplement used to support other streams of data at present. Techniques are being developed to provide test site specific calibrations of the software leading to more reliable outcomes. There are numerous benefits associated with establishing WaMoS®II system for tidal current measurement. At EMEC the system has provided an additional stream of data which adds to increased site characterisation. The system has been key in identifying flow patterns of previously unknown current patterns, particularly at the wave test site where current measurement was not the initial priority. The WaMoS®II data stream has also been provided to developers that are present on EMEC’s test sites providing them with a near-real data feed of live conditions on-site. This can be particularly useful when local weather conditions are extreme. As the surface current and direction are equated from the wave height measurements wave effect on tide and vice-versa can be established. The radar installation can be more cost effective than ADCP network with a good percentage of availability.

While undoubtedly there are benefits associated with the WaMoS®II radar system there are disadvantages that must also be considered. While calibration methods are generally well established for the WaMoS®II system there tends to be scatter when comparing results from other sources. EMEC are developing unique quality control and calibration routines to increase the quality of the data. Measurements from the radar are representative of a relatively large spatial area comparisons with in-situ type measurement devices, such as ADCPs and Waverider buoys and cannot be considered as accurately comparable which makes the calibration process more difficult. The signal to noise ratios decreases with distance so quality of the data at the fringes of the radar range become less reliable.

While the availability of the radar has so far been reasonable surface current and direction may only be obtained when the primary wave quality, wind speed and direction are favourable.

The radar data feed has already been utilised by developers at the EMEC test sites suggesting that there is a demand for the outcomes of the WaMoS®II radar system. EMEC has spent the last 18 months integrating the WaMoS®II system into the regular data collection and analysis routines although there are still a number of areas that have the potential to be developed. Quality control of the data have already been mentioned but according to
some preliminary analyses there are a number of other potential areas that could be developed. These include: constituent mapping; harmonic analysis; shear zone detection from sea surface roughness; tidal current prediction and tidal phase mapping.

3.6 References


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Mccann, D., & Bell, P. S. (2013). Knowledge exchange: Field demonstration of the capabilities of x-band radara for coastal remote sensing. NERC.
4 REVIEW OF PROCEDURES/EXPERTISE IN FIELD TESTS OF MARINE ENERGY TECHNOLOGIES->IMPACT FOR FIELD TESTING OF TIDAL ENERGY DEVICES.

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4.1 DEVICE RELATED PARAMETERS TO BE MONITORED

When undertaking in-sea tidal energy device testing, the parameters against which the in-sea performance will be assessed need to be clearly defined together with the appropriate instrumentation selected. This should form a core part of the ‘Design of Experiment’ process, in which the objectives of the testing program are defined; the specific environmental conditions the testing will be undertaken quantified; the operational program the plant will undergo pre-defined; the parameters to be monitored and recorded identified including the spectrum range of data to be recorded; the instrumentation type and model number together with the measurement range required in order to capture the performance envelope of the system being tested. In addition the ‘Design of Experiment’ should record the data frequency and format, the processing methodology to be applied to the ‘raw’ data and the format to be used in the interpretation and presentation of device performance data.

When considering the deployment of a tidal energy converter and the types of performance metrics to be captured during a testing program in order to establish the performance envelop of the test specimen, the following basic performance evaluation metrics should be captured:

- \( \frac{C_p}{\text{Lambda (TSR)}} \)
- \( \frac{C_t}{\text{Lambda (TSR)}} \)
- Device station keeping stability/ motion in flow; and where possible
- Rotor blade root loads.

The \( \frac{C_p}{\text{Lambda (TSR)}} \) parametric (Tip Speed Ratio) identifies the efficiency at which the rotor will convert the hydrokinetic power within a tidal flow in to useful mechanical power, as shown in figure 1. This also characterise how variations in rotor speed as a result of non-optimum torque control on the rotor shaft will impact on the efficiency. This enables the control strategy for the rotor to be developed in order to maintain peak efficiency and identifies the critical level of control needed to be applied in order to maintain maximum rotor efficiency within a reasonable operating spectrum. This should also consider the severity of performance drop off should rotor control become compromised.
Identifying the Ct/ Lambda (Tip Speed Ratio) parametric, as shown in figure 2, identifies how operating the rotor at a specific efficiency impacts on the thrust load experienced by the rotor blades and power transfer system. This information will inform the structural design of the rotor and drive train system to ensure it can maintain system integrity for the spectrum of operating conditions the test specimen will be exposed to.

Device stability and the effectiveness of motion control within the tidal flow should be monitored to establish whether the test sample can maintain its station keeping within the flow. Additionally, this will allow monitoring system response so that oscillations or vibrations are not being introduced. Structural vibrations can compromise the energy conversion efficiency or structural integrity of the rotor and power train system. This level of monitoring can be achieved by the inclusion of appropriate accelerometers/ inclinometers, as shown in figure 3, within the body of the nacelle. This type of accelerometer detects the motions and movements. Through mapping to three coordinate positioning the risk of compromise to the power generating performance will be identified. Further, with a Fast Fourier Transformation (FFT) of the data critical frequencies associated with the operation of the device and critical responses to specific load conditions can be identified.
Monitoring of rotor blade root loads provides information on the levels of load being experienced at the fluid, power capture interface. This level of monitoring will ensure these loads and resulting bending moments remain within the design envelope of the rotor/blade system. Where appropriate the structural integrity of this system can be controlled by varying the rotor operating conditions. If applicable, rotor control can be enacted which will alleviate any compromises to the rotor/power capture interface and to an extent that failure of the power capture interface and drive train components are mitigated.

To enable the performance of the test specimen to be established and performance ‘Bench Marking’ to be completed, it is vital to monitor and establish the hydrokinetic power within the tidal resource the test specimen will be deployed and operated in. Knowing the hydrokinetic flux within the resource and the performance of the tidal energy converter, the performance metrics discussed can be established. These metrics can also be used to establish a ‘Bench Mark’ of device performance for future reference and comparison with other similar technologies. The variability of the resource and sensitivity of the instrumentation used to quantify each of these performance parameters needs to be incorporated so that tolerance levels within the data can be identified. This should be included within any analysis of device performance data so levels of accuracy in both the performance analysis and ‘Bench Marking’ can be quantified and hence confidence in the data presented established.

4.2 REVIEW OF CURRENT FIELD MEASUREMENT PRACTICE FOR TIDAL TURBINE TESTING

This section will review current practices for measuring tidal currents in the field. Limitations of the methods are discussed and the impacts that these have on testing of tidal energy devices will be highlighted.

Detailed characterisation of the tidal flow in the field is important because of its high variability, both spatially and temporally, which has a direct impact on turbine performance (power capture) and the magnitude of structural loads. Vengatesan et al. (2011) list some key causes of the variation in the tidal resource:

- Tidal constituents
  - spring-neap cycle
  - solstice/equinox cycle
  - 18.6 year cycle due to moon’s orbit
- Weather patterns
  - surge due to storms and hurricanes
Kofoed et al. (2010) note some additional factors:

- local bathymetric effects
- wave motion
- wind driven currents

This demonstrates that the variation in tidal flow is problem of many parameters, and it is associated with a wide range of spatial scales and time periods. This makes it a challenging problem to model numerically. It is also difficult to design a measurement technique for using in the field, which captures the flow properties relevant to both the short and long term operation of a tidal energy device.

Currently, the most common method for characterising the flow field at a site is to deploy an acoustic Doppler current profiler, ADCP (or ADP) device. These can be installed in either a towed configuration or on a static mounting, usually on the seabed, although surface buoys or subsurface buoy mountings are other options.

Towed systems enable a larger area of the site to be characterised, providing an assessment of the spatial variability of the flow. This is particularly important for array developments but is also useful for understanding the flow characteristics at single devices. Static mounted systems provide measurements only locally to the proposed device testing location, but give greater detail of the flow. Static surveys can be deployed for a longer time period than towed surveys so that the data will be representative of a wider range of conditions. Static surveys are conducted both pre-deployment and during the testing period of the tidal energy device, while towed surveys are usually completed in the pre-deployment stage.

Reports have been produced with the objective of standardising the methodology for tidal energy testing by EMEC and ORNL; leading research centres that are specialised in renewable energy, as well as by the larger research project consortia such as Equimar and Marinet. The reports provide guidelines and recommend best practices for resource characterisation and flow measurements, both pre-deployment and during field testing of tidal energy devices, see Elsaesser et al. (2013), Holmes et al. (2011), Ingram et al. (2011), Neary et al. (2011), Vengatesan et al. (2011) and Legrand (2009). These documents give an overview of the working principles of the measurement devices, deployment methods, length of deployment, data acquisition systems (storage and transfer), recommend measurement device operation parameters, and consider the reliability of the data, including data processing techniques and treatment of uncertainty. There is general agreement between the reports, and a short summary of the advice for use of ADCPs in the field is set out in the following:

- Deployment time
  - Absolute minimum deployment time of a static mounted device should be 1 month but 3 months is preferable. It should be noted that 30 days of data only allows detection of tidal constituents with a period of 15 days or less, so longer period constituents will not be recorded (Holmes et al., 2011).
  - Shorter survey times (<1 month) may be appropriate at the early stages of resource characterisation i.e. for initial assessment of a site (Legrand, 2009).

- Data collection and record keeping
  - The importance of comprehensive record keeping of test conditions and data processing techniques is highlighted across the reports, and best practices are recommended.
  - Options for data collection, storage and transmission systems are discussed in detail. Holmes et al. (2011) note that much of the advice associated with data collection practices is based on real experiences in the field with deployed devices such as SeaGen, CoRMaT and OpenHydro. These early deployments brought to light a variety of issues which would be difficult to foresee otherwise.
• Spatial resolution
  o The vertical bin size should be of the order of 1m, although Holmes et al. (2011) recommend reducing the bin size to 0.5m if the water depth is less than 20m.

• Sampling frequency
  o The sampling frequency should be at least 1Hz for static deployments, and Legrand (2009) recommends a frequency of 2Hz for towed surveys.

• Location of static devices
  o Elsaesser et al. (2013) recommend deploying two ADCP devices simultaneously, one on the flood side and one on the ebb side of the turbine. A second option is to place two ADCP devices in line with the turbine to the port and starboard sides.
  o The ADCPs should be located at a distance of between 2 and 5 rotor diameters upstream and downstream of the turbine or if in a side by side arrangement, at a distance of 1-2 rotor diameters from the edge of the turbine.

• Length of data collection for averaging
  o 5-10 minutes of continuous data should be used to calculate an average velocity value for each measurement point in time, however it may be sufficient to average the data over a 1 hour period during the initial stages of resource characterisation (Vengatesan et al., 2011).
  o It is important to record the instantaneous data as well as the time averaged data because it may be possible to obtain an estimate of the level of turbulence from this data for better characterisation of the flow. This is relevant to some aspects of the turbine design such as determining the maximum blade loads as well as fatigue considerations.

• Survey transects
  o Survey lines should be conducted in both directions to alleviate bias towards the ship motion. Legrand (2009) notes that a moving boat can influence the velocity by ±5cm/s.
  o It should take no longer than 10 minutes to run a transect in both directions in order for the assumption of a constant flow field during the measurement to be valid.
  o The direction of the survey should be perpendicular to the flow (Vengatesan et al., 2011)

• Accuracy
  o Legrand (2009) states that the standard deviation of the velocity data should be < 5cm/s and the error in the device positioning should be no more than ±5 degrees.

• Additional data collection
  o To characterise the tidal flow the elevation of the water surface also needs to be measured, and ADCP devices often have in-built pressure sensors or acoustic surface tracking technology to do this.
  o ADCPs may also be used to collect wave data, but this requires much higher frequency of water surface measurements than is needed to obtain the tidal elevation.
  o Wave measurement and analysis techniques are covered in detail by Vengatesan et al. (2011).

It is important to note that field surveys conducted following these guidelines will not produce a fully comprehensive record of the flow field, and the reports referenced above discuss in detail the linkages between harmonic analysis (analytical method for assessing tidal level and velocity), numerical modelling and field data. An analysis using all three methods will produce the most complete understanding of flow conditions across the whole site over a wide range of timescales (i.e short term through to long term variability). The field data provides verification of the
numerical models. These can then be used with confidence to predict flow patterns over a wider area and to produce longer term data which would only be possible with very long deployments in the field using multiple devices, which is impractical. Tidal constituents can also be obtained from the field data for input into the analytical modelling (Legrand 2009). The effects of waves and weather events, turbulence and bathymetry are captured in the field data, aspects which cannot be modelled in a harmonic analysis, and only with limited success in numerical models. This point is illustrated by Thake (2005) who presents a comparison of ADCP field data with a harmonic analysis prediction. Although the overall trends are similar, the harmonic analysis does not capture all of the events shown in the ADCP signal. Field data is critical to understanding the finer details of the flow characteristics and allows an assessment to be made of the limitations of the numerical and analytical models.

4.2.1 Limitations of ADCP

According to Homes et al. (2011), the popularity of ADCP technology for field measurements is mainly due to the equipment being relatively inexpensive and easy to manoeuvre. A unique quality of ADCP technology is its ability to obtain measurements of the flow characteristics at different depths in the water column simultaneously. ADCP also has the advantage of being a reasonably well established technology which has been used quite extensively in the field, especially in riverine environments. Consequently there is a considerable amount of literature available on the subject. Measurement protocols have been developed by organisations such as the Water Survey of Canada (2004) and the U.S. Geological Survey (Oberg et al., 2005). Assessments of the measurement accuracy of ADCPs in river and coastal locations have also been conducted, see Oberg and Mueller (2007) and Jimenez-Gonzalez et al. (2003), providing confidence in the use of the technology in a wide range of applications.

While there are many benefits to choosing ADCP, the technology is not without its limitations and it is important that these are properly understood and taken into account when using data derived from ADCP measurements. The main limitations are discussed below, and the impact that these limitations have on the testing of tidal energy devices is considered in section 4.3.

4.2.2 Spatial resolution

The spatial resolution of an ADCP device depends on the sensor design because this dictates the degree of beam divergence through the water column. The sampling volume will increase with distance from the sensor, so that the spatial resolution is not constant with depth. According to Terray et al. (1999) the typical beam orientation in an ADCP device is of the order of 20-30 degrees from vertical, resulting in the majority of measurement bins being several tens of meters cubed in volume. Even devices considered to be ‘high resolution’, such as those discussed by Osalusi et al. (2009), have a spacing in the order of 10m between opposite beams. When comparing the measurement volume to the typical dimensions of a turbine, it is apparent that the resolution is not fine enough to capture all of the pertinent features. As noted by Neary et al. (2011) large sampling volumes will not characterise small scale flow structures correctly, and large sampling volumes may miss spatial changes in the flow field.

The vertical resolution of an ADCP is user selectable within a certain range. While a finer vertical resolution is central to obtaining high quality vertical velocity profiles, increasing the vertical resolution results in a lower signal to noise ratio (more noise). Therefore, the vertical resolution has to be compromised to a certain degree.

4.2.3 Temporal resolution

In order to produce representative average flow conditions over time, the length of velocity time history data used in the averaging is critical. Time-averaged data is independent of the influence of turbulence, but only if the averaging time is long enough, and this depends on the level of turbulence present in the flow. Conversely, the longer the time
period, the less valid the assumption that the flow field has remained unchanged during the averaging period. Hence a balance must be struck, and the data will, therefore, be influenced by both of these factors.

4.2.4 Device frequency

The frequency of the device determines in part the spatial resolution of the measurements. Higher frequency devices produce higher resolution data, but the frequency also affects the vertical range of the measurements, as higher frequencies attenuate more quickly in the water column. Neary et al. (2011) note that a balance is needed between the measurement accuracy and measurement distance: high frequency devices will produce data with lower uncertainty but over a smaller distance. Therefore, Vengatesan et al. (2011) recommend using high frequency devices (>1MHz) only in shallow water sites.

4.2.5 Data acquisition systems

Errors can be induced by the data acquisition systems themselves. In particular, there are often issues with the synchronisation of different data streams, and the accuracy of internal clocks. Ingram et al. (2011) warn that using lots of separate systems makes data integration and synchronisation challenging. However, separate systems may be preferable for other reasons such as to improve the reliability of the system.

4.2.6 Data processing and corrections

Noise often has a significant impact on acoustic measurements. Factors that affect noise are the vertical bin size, ADCP frequency, instrument model, flow velocity, type of particles in the flow, turbulence and the choice of ambiguity velocity (Neary et al., 2011). Hurther and Lemmin (2001) provide a more detailed explanation of the sources of noise in ADCP signals.

Because of the inherent noise in the signal the velocity data should not be used in its raw form, as it will not be characteristic of the true flow conditions. A considerable amount of research time has been invested into developing processing techniques to remove the influence of noise and other forms of interferences from the raw velocity data. Data processing techniques for ADCP data are discussed quite extensively by Gunawan and Neary (2011).

Another reason for applying processing techniques to the data is to compute turbulence statistics for the flow (see section 4.2.12 for further details). It is important to note that all forms of data processing techniques have their own limitations, and as such will affect the quality of data produced.

4.2.7 Spurious reflections and interference

As acoustic devices work by detecting the reflection of acoustic waves by solid objects (particles) in the flow, there is the possibility that spurious reflections will be detected. This could be due to the presence of boundaries, or other solid objects in close proximity to the measurement volume such as fish. Another source of interference can be caused by ‘cross-talk’ between devices if they are in close proximity to one another and operating at integer multiple frequencies (Neary et al., 2011). As with the treatment of noise (see section 4.2.6), an attempt can be made to identify these effects in the raw data and filter them out by applying specific processing algorithms (Vengatesan et al., 2011).

4.2.8 Validity of assumptions inherent in ADCP

The use of 3 separate acoustic beams to define a measurement volume necessitates the assumption that the flow field is uniform within that volume. However, this may not be the case, especially if the dimensions of the sampling volume are quite substantial. To monitor the validity of this assumption during data acquisition, many ADCP devices
are built with 4 acoustic beams, providing a redundant velocity component which can be used to estimate the error in the ADCP beam measurement.

4.2.9 Calibration

Device calibration can be another source of error in the data. Although ADCP sensors are calibrated by the manufacturer prior to sale, it is important to understand the limitations of this calibration, and to ensure that the instrument parameters have not shifted over time. Shih et al. (2000) conducted calibrations in the laboratory of a range of ADCP products and found that in most cases the measurement errors were slightly larger than those specified by the manufacturer. Ingram et al. (2011) recommend conducting a calibration both pre-device deployment and post-deployment to account for any deviations that may have occurred during testing. Unfortunately, choosing a practical and efficient methodology for device calibration is not trivial. Oberg (2002) discusses the different calibration methods and the advantages and disadvantages associated with each option.

4.2.10 Mounting and station keeping

The way in which the measurement device is mounted is critical to the accuracy of the data collected. Even static bottom mounted systems have many issues associated with positioning and station keeping. Flow induced vibrations of the equipment may be substantial particularly in strong flows, and these vibrations will have an influence on turbulence statistics computed from the data (Neary et al., 2011). There is also the possibility that the device is moved out of position during deployment, due to the strength of the flow, scouring of the seabed around the mounting (see Osalusi et al., 2009), or due to impact from debris or shipping equipment. For this reason Ingram et al. (2011) suggest deploying ADCP on an anti-trawl seabed mount to reduce the risk of damage from vessels.

Station keeping is particularly problematic for floating devices. While floating deployments save diving time and are more manoeuvrable, Elsaesser et al. (2013) note that strong currents cause excessive movements of equipment in this configuration.

The alignment of an ADCP device should be perpendicular to the flow direction so that the boundaries between the vertical bins are horizontal. Unfortunately, perfect alignment is challenging in the field, especially for towed systems. Even small angles of tilt can reduce the accuracy of the velocity measurements quite significantly (Simpson, 2001). In-built sensors can be used to monitor device pitch and roll and corrections should be applied to the data to take this into account.

4.2.11 Reliability

With long deployments of 1-3 months, in harsh environments, the likelihood of encountering hardware problems and consequent data loss is high. This can occur in the device itself, or in the data storage and transmission systems. Due to the high cost of field trials, especially during the turbine testing stage, it is not practical to simply re-run the test to make up for periods of lost data. Therefore, it is important to integrate a degree of redundancy into the measurement system.

Redundancy is built into many devices in the form of a 4th acoustic beam, as one beam can fail without affecting data collection. Furthermore, multiple ADCP devices can be deployed to build redundancy in the measurement strategy at the same time as improving the data coverage and improving confidence in the data (Legrand, 2009). As Holmes et al. (2011) note, the cost of deploying extra devices is small as there is no difference between the infrastructure needed to deploy one or a number of devices.

Holmes et al. (2011) suggest building redundancy during device testing by employing other direct and indirect measurement techniques in conjunction with the ADCP devices. Thake (2005) reports the outcomes of a turbine sea trial where this approach was taken.
4.2.12 Turbulence measurement

A key limitation of existing ADCP technology is that it is difficult to accurately measure the turbulence characteristics of the flow. Obtaining measurements of turbulence from ADCP data is an area of active research, some of the state of the art of which is discussed in previous sections of this report (see section 2).

One issue is how to obtain the true turbulence data from the raw velocity signal, as the raw signal includes other contaminating components i.e. from Doppler noise and instrument motion (Neary et al., 2011). Neary et al. (2011) also point out that assessing turbulence is challenging because the flow is non-stationary. This can make it difficult to choose a measurement frequency which gives a high enough resolution to assume stationary flow during the sampling time whilst ensuring the sampling period is long enough to account for noise properly.

The coarse spatial resolution of ADCP measurements significantly limits the accuracy of the turbulence data that can be obtained. This is especially relevant to turbine testing because the scale of the measurement volume is likely to be of a similar order of magnitude to the dimensions of the turbine, and therefore, many of the scales of turbulence of interest for this application cannot be monitored. Higher frequency devices would improve this, but at the cost of measurement range and greater power requirements. For example Osalusi et al. (2009) used high resolution ADCP to investigate turbulence but only in the bottom boundary layer of the flow. Norris and Droniou (2007) discuss initial results of using high frequency ADCP to measure wave-induced velocities and bottom boundary layer turbulence, and tried to separate these effects, but only for a short time period of data collection. Furthermore, evaluation of high frequency ADCP for turbulence measurements in the laboratory have shown there are significant limitations in terms of measurement accuracy (Nystrom et al., 2007). This indicates that further research is needed before ADCP can be used to comprehensively quantify turbulence in the field.

4.3 Impacts on tidal testing

The limited spatial resolution of ADCP technologies and the resulting lack of detail in the measurements of the velocity profile and spatial variability of the flow have a significant impact on the results of tidal energy device testing. Maganga et al. (2010) showed in the laboratory that turbulence has a substantial influence on tidal turbine performance. Furthermore, tidal flows in the field usually contain significant levels of turbulence. For example both Thomson et al. (2010) and Sutherland et al. (2012) measured turbulence intensities of around 10% at different field locations. However, the low spatial resolution of ADCP devices means that they are not able to fully characterise this aspect of the flow. Turbulence is one of the complexities in the field that is difficult to model in the laboratory in a representative manner. Therefore, it is important to test devices in the field as well as in the laboratory to enable a comparison of 'controlled' environments with 'real' sea conditions in order to improve turbine performance prediction techniques. Unfortunately this is not possible if the turbulence characteristics cannot be measured with any great certainty or detail in the field. Although attempts have been made to improve the capabilities of ADCP technology for turbulence measurements, see section 4.2.12, more extensive development is needed before this methodology is established in practice.

Another possible impact of using ADCP devices for flow measurement is the potential for interference between the measurement device and the turbine. Intrusive equipment will affect the flow in its proximity (see Mueller et al., 2007), ultimately influencing the turbine performance data. However, if the scale of the measurement equipment is order of magnitudes smaller than the turbine or located away from the turbine energy capture area this impact will be small. Consequently, careful consideration should be given as to the specifications and dimensions of the sensor used, the position of the equipment in relation to the turbine and the type of mounting for the device. There may be a resulting trade-off between the resolution of the measurements and the degree of interference with the turbine as the higher frequency ADCP devices have a smaller measurement range so must be located in closer proximity to the turbine.
The reliability of the measurement system is a key to a successful and cost effective tidal energy testing program. Incomplete or unreliable measurement data will have a substantial negative impact on this. The stakes are high for field testing programs so uncertainty in the measurement data must be monitored and kept at an appropriate level. However, the wide range of possible sources of error, discussed in section 4.2, makes the overall uncertainty very difficult to quantify. Further research to assess and reduce ADCP measurement uncertainty, both with regards to technical and practical considerations, would be highly beneficial for future testing programs.

4.4 DEVELOPING TECHNOLOGIES

Section 4.2 discussed in detail the use of ADCP in the field for tidal current measurement. The reasons for the extensive uptake of this technology were presented, but some key limitations were also highlighted. This demonstrated the potential for improvement in a number of areas, and the following sections, 4.4-4.5, will discuss how this could be achieved through the development of both existing and new technologies. Some alternative technologies that have been deployed albeit less extensively in the field will be outlined, before considering the suitability of some of the techniques currently used in different applications and at different scales in the field and in the laboratory. To conclude, suggestions for the direction of future developments will be put forward and the ways in which advancements in the technology can overcome the limitations and impacts on tidal energy device testing will be considered.

First some existing technologies that have been used in the field as an alternative to ADCP sensors for measurement of tidal flows are discussed.

4.4.1 Flow meters

MacEnri et al. (2013) present the results of a tidal turbine field test in which the current was measured using an electromagnetic flow meter located at hub height. Flow meters provide a point measurement of the velocity, but at sites where the flow is known to be reasonably uniform across the diameter of the turbine, this may be an appropriate method for monitoring the inflow conditions. Flow meters are less expensive and have the advantage of being simpler to deploy and operate than acoustic devices.

There are a wide variety of flow meters on the market. Some are mechanical based systems consisting of an impeller and a built in compass to measure flow speed and direction, others use the principle of induction by measuring the electric current due to the flow of water through a magnetic field. Joseph (2013) provides an extensive review of the different types of flow meters as well as many other ocean current measurement technologies.

Although flow meters are used primarily for velocity measurement, Sanford (1999) extended the capabilities of an electromagnetic flow meter to obtain measurements of vorticity as well as velocity. By measuring both the first and second derivatives of the electric potential field, the linear velocity components and a component of water vorticity were determined.

4.4.2 Radar

Radar is another technique that has been used in the field for characterising tidal energy sites (see Ingram et al., 2011 and Vengatesan et al., 2011), but only to obtain surface velocities. The methodology and the state of the art of this technology are discussed in detail in chapter 3 of this report.

4.4.3 ADV

ADV devices have been used quite extensively in the field, and the technology was discussed in detail in section 2. Neary et al. (2011) state that ADV is well suited to measuring the mean flow and some turbulence characteristics at
discrete points, but the biggest challenge in the field is how to stably deploy the device as the probes are generally slender in design. The main advantages of ADV are its high frequency and its small sampling volume of the order of 1cm$^3$ so that the assumption of homogeneity within the sample volume is much more valid than with ADCP. However, in contrast with ADCP it only gives a ‘point’ measurement of the flow which is a disadvantage when measurements over a large scale are desirable in the field. As ADV and ADCP work on similar principles, they share many of the same limitations, particularly in terms of data processing. Gunawan et al. (2011) provide an extensive discussion of ADV data processing techniques. Several comparisons have been made between ADCP and ADV velocity and turbulence measurements in the field, Neary et al. (2011), Sutherland et al. (2012), Thomson et al. (2010) and Thomson et al. (2012) showing reasonable agreement between the two.

4.5 Suitability of Technologies from Other Contexts

In this section the potential of a range of technologies to be used for tidal energy field testing will be considered. These are technologies which are currently used for other applications in the field, particularly at other scales, and also technologies that are used more typically in a laboratory setting.

4.5.1 ROVs and AUVs

The potential for ROV and AUV technologies to be used in the tidal energy application is discussed by Elvander and Hawkes (2012), Elvander and O’Halloran (2013) and Omerdic et al. (2010). ROVs are generally used in difficult environments to mitigate the use of divers, i.e. in deep water, for inspection and maintenance operations. AUVs are a complimentary technology designed for conducting high quality surveys over wider areas. These systems are not measurement devices in themselves but are essentially sophisticated mobile mounting platforms for existing measurement equipment. They have the advantage of being highly mobile, and enable a multitude of measurement types to be made from the one craft. According to Elvander and Hawkes (2012) AUVs can be built with an extremely high accuracy positioning system, and this is a key advantage of the technology as high quality measurement data is dependent on high accuracy navigation systems and stable vehicle dynamics. AUVs can be built to be quite compact and the systems discussed by Elvander and Hawkes (2012) range from 9-21 inches in diameter, and 1-8m in length. It is, therefore, possible for these devices to be reasonably non-intrusive in the tidal application and measurements in fairly close proximity to the turbine would be possible.

Elvander and O’Halloran (2013) note some of the limitations of ROV and AUV technologies:

- The maximum speed of the vehicle (usually up to 2 knots), makes it time consuming to collect a series of data over a survey site
- These types of devices commonly have difficulties with station keeping in strong currents which is a major challenge for the successful application of the technology to sites identified for tidal energy developments
- Many systems use video cameras as feedback sensors making them ill-suited to sites with low visibility
- Vehicles often need a dedicated deployment craft which increases the operation costs

Recent technological improvements have been focused on resolving some of these limitations. Elvander and O’Halloran (2013) discuss the use of sonar instead of video sensors to facilitate successful operation in water with low visibility. They also reported new technology with a higher maximum speed of up to 6 knots. Omerdic et al. (2010) made improvements regarding vehicle station keeping in strong currents, and re-designed the deployment method to increase flexibility and reduce costs. They also improved the system reliability by implementing a fault tolerant control system.

4.5.2 Optical techniques

Optical techniques such as LDV and PIV have been used extensively in laboratory flumes for a wide range of applications including for the measurement of flow properties in the context of tidal energy research (see Maganga et al., 2010 and Good et al., 2011). LDV provides high accuracy velocity measurements averaged over a very small sample area and avoids many of the issues associated with acoustic methods. PIV is unique in that it allows measurements with high spatial resolution to be obtained simultaneously at multiple locations in the flow field. This
means that the spatial gradients in the velocity are captured enabling direct measurement of the turbulence characteristics, which is not possible with point measurement devices such as LDV and ADV (Wang et al., 2013). Unfortunately, it has proven challenging to implement these technologies in the field. Wang et al. (2013) attribute this to the high power and computing requirements, and the complexity of the optical configurations.

Agrawal and Aubrey (1992) reported one of the few attempts to deploy a submersible LDV system in the field, at a coastal site in only a few meters of water. They noted that the success of the measurements depended heavily on underwater visibility, even with a distance between the measurement volume and the laser probe of only 1m.

There have been a greater number of attempts to design PIV systems suitable for the marine environment, and this is still an area of active research. For example, Liao et al. (2015) (also see Liao et al., 2009) developed an underwater miniature PIV system to measure near-bed and near-surface flow characteristics. They found excellent agreement between measurements with this system and an ADV probe. They used a battery powered laser so that the measurement system was self-contained on an underwater platform. They found that there was adequate natural seeding for the measurements, but reduced visibility prevented data collection when a large amount of suspended sediment was present. Their system used a very small scale measurement area of 11.5x7.8cm, limiting the suitability of the system for measurements in the main body of the flow.

Wang et al. (2013), Nimmo Smith (2008), Nimmo Smith et al. (2002) and Doron et al. (2001) also developed underwater PIV systems for use in the field. The configuration with the largest measurement area is reported by Nimmo Smith et al. (2002) at 0.5m², and by using an extendable bottom mounting system they were able to collect measurements at a range of depths in the water column. In contrast with the system of Liao et al. (2009) the main laser in this system was kept on the ship and connected to an underwater probe via fibre optic cable. This prevented the need for a battery and waterproofing of the expensive optics system.

An alternative field methodology based on PIV, known as large-scale particle image velocimetry (LSPIV), is described and reviewed by Muste et al. (2008). This approach is gaining acceptance for flow measurements in riverine environments amid ongoing research. LSPIV does not require use of a laser so it is much simpler to deploy than underwater PIV and it is a non-intrusive technique as the equipment is not in contact with the flow. However, similarly to radar systems it only provides direct measurement of the velocities at the water surface. In comparison with radar, LSPIV has the advantage of using compact and readily available equipment (a video camera) and hence has a high degree of mobility. LSPIV has been used to survey areas of rivers at a range of scales from 100-5000m², so it has excellent spatial coverage alongside high spatial and temporal resolution, enabling both velocity and turbulence characteristics to be captured. The main limitations on the accuracy of LSPIV are its ability to cope with a range of lighting and natural seeding conditions. However, systems have been proposed to mitigate the reliance on seeding such as that of Fujita et al. (2007) who obtained surface velocities by considering light intensity patterns in the images. Another issue with LSPIV is that the camera usually has to be positioned at an oblique angle to the water surface. Although images can be rectified as part of the processing, there will be a reduction in accuracy compared to a set-up with a camera perpendicular to the measurement plane. Muste et al. (2008) reported differences of up to 10% between LSPIV point velocity data and ADV measurements, but the agreement improved considerably when comparing LSPIV to ADCP and flow gauge discharge measurements.

4.5.3 Alternative configurations for acoustic technologies

Hurther and Lemmin (2001) investigated an alternative ADCP sensor configuration in the laboratory to improve turbulence measurement capabilities. By using a high frequency (1MHz) system with one vertical beam they achieved a 7mm sample width without divergence but only over a small range (approx. 60cm). Four receivers were positioned at angles to the vertical beam to make profiling possible and resulted in a significant improvement of measurement accuracy over traditional ADCP. While this is a promising technique, further development would be needed to increase the measurement range before it could be usefully deployed in the field.

4.5.4 Possible direction of future developments

Some key areas for development identified from the discussion in the previous sub-sections are:
• Deployment methods (cheaper and more flexible systems)
• Manoeuvrability of measurement equipment
• Station keeping particularly in the strong flows expected in locations appropriate to tidal energy development

The advancement of measurement techniques should also focus on developing systems which operate without compromising on either the spatial resolution or spatial coverage of measurements so that turbulence characteristics as well as velocity can be measured at the full range of scales relevant to the performance of tidal turbines.

4.5.5 Ways to overcome the current limitations of measurement practices in the field

This section concludes by drawing on the previous discussion to propose ways to address the limitations discussed in section 4.2 of this report with regards to current tidal flow measurement practices in the field.

Firstly, AUVs have the potential to dramatically improve station keeping and manoeuvrability of measurement systems, while the compact design may lead to a reduction in intrusiveness of the equipment with the flow. High manoeuvrability would enable higher resolution acoustic devices to be employed, improving the quality of data. AUV systems can also lead to the provision of a more comprehensive data set as the device can be fitted with a number of instruments.

Secondly, further development of underwater PIV systems for the field has the most potential to produce high quality turbulence measurements. It is anticipated that PIV will become more suitable for the field in conjunction with developments in laser technology and computing power. Another area for development is increasing the measurement area while maintaining spatial resolution so that measurements are possible at scales more suited to field sites. However, at present smaller measurement areas could still be used to obtain high detail flow measurements in close proximity to the turbine, or at specific areas of interest. There may also be potential to deploy a PIV based system on an AUV combining the advantages of both systems.

Finally, in the shorter term it is recommended to employ a combination of the measurement techniques discussed in this report to build a comprehensive measurement system which covers a range of scales, with a high level of redundancy.

4.6 REFERENCES


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5 APPLICATION OF REAL/FIELD CONDITIONS TO TANK/MODEL SCALE TESTING

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In this section, issues and limitations of model tests reproducing at laboratory scale real-life conditions experienced by marine current devices deployed at sea are discussed. Dealing with hydrodynamics, the term “laboratory scale” tests denotes here experimental work conducted in towing tanks, flume tanks, circulating water channels or similar confined-flow facilities where scaled models of devices are analysed. For the sake of conciseness, in the following all these facilities will be referred to as *towing/flume tanks*.

The scale ratio between model and full size is usually defined according to the purpose of testing, and the stage of development of the concept (Technology Readiness Level, TRL). Small models with typical scale ratios in the range 1:25 to 1:50 are used for concept validation at early stage of development (TRL 1-3), whereas larger models up to 1:10 scale with respect to full size are used at following development stages (TRL 4-5) to validate and optimize a preliminary design and to analyse device subcomponents like the PTO system. Higher values of TRL typically pertain to field tests for prototype demonstration in real or simulated operational environment.

The complementarity between field tests performed on prototype-scale devices deployed at sea and laboratory tests conducted in confined-flow facilities is discussed in other MaRINET Deliverables and is not repeated here, see e.g., Deliverables D2.2 and D2.7. In addition to that, Deliverables D2.23 and D2.24 present comparisons of testing marine current devices in facilities of different types.

The following discussion mainly refers to turbine systems, where the conversion of current kinetic energy into mechanical energy is actuated by means of rotating blades. Nevertheless, the discussion can be easily transferred to model tests for non-turbine systems like oscillating foils, kites and vortex-induced vibrating cylinders.

The analysis here is focused on tests devoted to the characterization of the hydrodynamic performance of devices, whereas testing other power train components including the PTO system are only briefly addressed. Related aspects are addressed, e.g. in the report and guidelines recently presented by the Specialist Committee on Hydrodynamics Testing of Marine Renewable Energy Devices at the Twenty-seventh International Towing tank Conference (ITTC), see Day et al. (2014). It is worth to observe that some members in this ITTC Committee are from organizations represented in the MARINET Project Consortium.

5.1 REPRODUCING AT MODEL SCALE REAL-LIFE OPERATING CONDITIONS

Routine towing/flume tank tests on small-scale models of marine current devices are usually limited to analyse uniform inflow conditions. This is a major deviation from real operating conditions, where a large amount of flow non-homogeneity and unsteadiness is observed. The amount of information that is derived by testing a device under idealised uniform inflow is then limited and some data necessary for a correct design of the system are missing. Specifically, fluctuations of current speed, direction and spatial profile determine transient hydrodynamic loads on the turbine and stress on device components that may have harmful consequences for the overall system reliability and survivability over the expected life cycle.

Main sources of flow unsteadiness are inherent to the energy resource of marine currents, as:

- flow turbulence
- interaction between current and surface waves
- bathymetry-induced flow deviations
- periodicity between ebb and flood phases in case of tidal (bi-directional) streams

In addition to that, non-homogeneous inflow to the rotor and transient blade and hub loads can be also caused by conditions related to actual device layout and installation:
• interaction among rotors and wakes in multi-device installations (clusters, arrays)
• rotor misalignment to the mean flow direction
• floating/moored turbine motions in response to hydrodynamic loads
• fluid-structure interaction effects (i.e. rotor blade hydro elasticity, VIV, ...)

Existing knowledge about the relationships between device performance/reliability and deviations of real-life operation from idealised conditions is still limited and towing/flume tank tests under unsteady, non-homogeneous inflow conditions reflecting as much as possible field tests observations is the subject of ongoing research and development of dedicated set-up and sensors.

Rather than trying to reproduce exact ambient conditions at sea, the purpose of laboratory tests is to analyse in fully controlled and repeatable environmental conditions, some specific aspect of the complex phenomenology observed from field tests. Here, model tests aimed at characterizing the following aspects are addressed:

• the effect of surface waves and wave/current interactions,
• the effect of turbulence and fluctuations of onset flow speed,
• turbine operation at yaw angle and interaction between rotor and supporting structures

Model tests aiming at investigating the aspects above require a detailed characterization of real-life conditions through dedicated measurements and data processing from field tests. Considering the effects of turbulence levels of the current flow incoming to the turbine, measuring techniques have been described in Section 2 above. Turbulence intensities along the mean flow direction as well as along normal directions should be determined with measurements repeated at different depths and different sea states. More specifically, the characterization of wave-current interactions implies that velocity profiles at increasing depths and different sea states and current speeds are determined, see Section 5. Axial as well as normal components of mean velocity and fluctuations should be recorded. Wave spectrum, wave direction with respect mean current direction should be recorded. The position of the device with respect to the current and its motions with respect to a reference position are also to be recorded.

5.2 EFFECT OF SURFACE WAVES AND WAVE/CURRENT INTERACTIONS

Depending on the facility type, the analysis of the effect of waves on the response of a marine current turbine involves one of the following arrangements:

a) model turbine towed if no current making devices are present
b) model turbine kept fixed in an onset current

The main difference between these two cases is that only in case b) the turbine is subject to a real current, whereas in case a) the current is simulated by the relative motion of the model with respect to tank water at rest, except for wave-induced motions. A major limitation of case a) is that the physics of the interaction between velocity fluctuations and turbulence generated by currents and waves cannot be investigated, whereas this is possible in case b). Nevertheless, tests in conditions a) allow analysing the effect of waves separating the interactions between wave-induced and current-induced turbulence.

In flume tanks and towing tanks planar waves are propagated in a direction parallel to the turbine axis. Turbine model installations with a small yaw angle are in general possible, whereas it is not possible to analyse the effect of waves propagating in different directions. Few rectangular or curved basins exist where a configuration with a model turbine subject to a current in one direction and waves propagating in different directions is possible.
Results of model turbines have demonstrated the existence of dynamic loading on turbine blades induced by wave-induced onset flow velocity fluctuations. In particular, wave excitations may induce fatigue loads; see e.g. results of work done at IFREMER (Gaurier et al., 2013).

In order to characterize transient loads induced by wave-induced velocity fluctuations, testing set-up has to include the possibility to measure time histories of thrust and torque at rotor hub. During tests, wave-induced velocity fluctuations incoming to the rotor are to be quantified through suitable velocimetry techniques. More complex installations are necessary to determine the relationship between blade load peaks and blade angular position over a revolution. To this purpose dedicated sensors are used like strain gauges that allow quantifying model blade deformations due to hydro elastic effects. Considering the small dimensions of rotor blades typically used for tank tests, e.g. blade span of 200-400mm, the application of this type of sensors is rather invasive and the effect on hydrodynamics performance should be carefully minimised.

More in general, measuring the effects of blade elasticity requires a careful set-up, calibration and analysis of scaling between model and full scale.

According to wave generation capabilities in the facility, the model should be tested in a wave spectrum reproducing field conditions. In order to ensure correct Froude scaling, tank limitations in terms of generated wave height and length determine a physical limitation to the size of the model that can be tested.

As an example, a 1:20 scaled 16 m turbine corresponding to a model rotor diameter of 800mm is tested in waves with amplitude of 200 mm corresponding to 8 m height crest to trough at full scale. Wave amplitudes in the order of 200 mm can be generated in several facilities. At the same sea-state, larger models would require higher wave amplitudes that only few facilities can cope with. Representative combinations of model size and maximum wave patterns can be derived from Table 6.1 above.

The decision about the size of the model being tested has to take into account that Froude scaling is not compatible with Reynolds scaling and this may have a serious impact on the correct scaling of hydrodynamic loads that are generated on turbine blades.

As an example, a model turbine with diameter $D = 800$mm, towed at speed $U = 1.0m/s$ yields ($R = D/2$ and kinematic viscosity of water, $\nu = 1.0 \times 10^{-6}m^2/s$)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Facility (TNA #)</th>
<th>Wave properties</th>
<th>Current properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strathclyde Univ.</td>
<td>Kelvin Hydrodynamics Lab</td>
<td>Unidirectional waves, Max. height of 0.5m</td>
<td>Towing speed 0-5m/s.</td>
</tr>
<tr>
<td>CNR-INSEAN</td>
<td>Wave tank</td>
<td>Unidirectional waves, Max. height of 0.45m; Wave length 1 to 10m</td>
<td>Towing speed 0-10m/s.</td>
</tr>
<tr>
<td>UEDIN</td>
<td>FloWaveTT (under construction)</td>
<td>Multi-directional waves, Max. height of 0.7m;</td>
<td>Current speed up to 1.6m/s;</td>
</tr>
<tr>
<td>Plymouth Univ.</td>
<td>COaST – Coastal Ocean and Sediment Transport Lab</td>
<td>Bi-directional waves, Max. height of 0.9m;</td>
<td>Current speed up to 0.2m/s, directed inline and across waves. Wind generation capability.</td>
</tr>
<tr>
<td>IFREMER</td>
<td>Flume tank</td>
<td>Unidirectional waves, Max. height of 0.3m; Peak period 0.5 to 2.0s;</td>
<td>Current speed 0.3-5.0m/s; Turbulence intensity 5-25%</td>
</tr>
<tr>
<td>CNR-INSEAN</td>
<td>Circulating water channel</td>
<td>No wave-maker. Project to add a wave-maker underway.</td>
<td>Current speed 0.3-5.0m/s; Turbulence intensity 3-5%</td>
</tr>
<tr>
<td>UNIFI-CRIACIV</td>
<td>Wave-current flume</td>
<td>Unidirectional waves, Max. height of 0.3m; Peak period 1.0 to 2.0s;</td>
<td>Bi-directional currents, flow rate 300l/s with 0.80m squared section.</td>
</tr>
</tbody>
</table>

*TABLE 6.1. Examples of facilities available in the MARINET Consortium for testing ocean current devices with combined current/waves simulation capabilities.*
4.11

Report new instrumentation and field measuring technology for tidal currents

**Re = UR / \nu = 4 \times 10^5**

Similar values of Reynolds number are critical in that an excess of laminar flow on rotor blades with respect to full scale conditions at higher Reynolds number is likely to occur. The resulting hydrodynamic performance coefficients like \(C_T\), \(C_Q\), \(C_P\) measured by model tests can be not representative of full size behaviour.

The correct scaling of Reynolds number can be an issue when the effects of both waves and onset flow turbulence are to be analysed from model tests. Results of wave/current interaction studies carried out at the IFREMER flume tank (Gaurier et al., 2013) demonstrate that the action of the wave maker produces a strong increase of turbulence levels of the flow incoming to the model rotor. The limited literature on this subject shows the importance of dedicated research in this area.

### 5.3 Effect of Turbulence and Velocity Fluctuations

The effects of current-induced turbulence to turbine loads can be investigated in flume tanks (e.g., Maganga et al., 2010) or in circulating water channels. In facilities of this type, the onset flow is characterised by a non-negligible amount of free-stream turbulence as a result of the action of impellers generating the water stream and of flow regularization devices placed upstream the test section.

Considering as example facilities among those available for Trans-National Access in the MARINET Project, free-stream turbulence levels of 3-5% are measured at the circulating water channel by CNR-INSEAN, whereas at the flume tank by IFREMER, turbulence is 5% using flow straighteners or higher values up to 25% by removing those devices. In contrast to this, towing tanks present a negligible turbulence intensity of the water stream incoming to towed models. In both flume/tank cases, turbulence grids can be designed to locally increase the turbulence intensity upstream the model. When natural turbulence is too high, honeycombs can be used to lower values. This subject is discussed in MARINET Deliverable D2.7.

The effect of background turbulence on turbine loads and power has been the subject of a detailed study in MARINET WP2 and WP4. In particular, a round-robin test of a 700mm tri-bladed horizontal axis turbine has been organized; see Deliverable D2.24 and Gaurier et al. (2014).

Turbulence intensity in test sections of facilities with currents generation capability are reasonably in line with real-life conditions observed from field tests. As a reference, turbulence intensity of an ocean/tidal current is typically in the range between 2-3% and 13-15%, whereas peaks of 25% and higher have been measured in river currents. Field measurements in tidal sites (see, e.g. Milne et al., 2013b) show that tidal stream turbulence is anisotropic with intensity in direction normal to the mean flow about half of the intensity in the main direction. The accuracy of turbulence measurements at sea using ADCP and ADV techniques is discussed in Mycek et al. (2014a). See also Sections 3 and 4 of the present report.

The importance of analysing the impact of onset flow turbulence on turbine performance is confirmed by results of tests show that turbulence intensity variations between 8% - 25% can determine model turbine thrust variations up to 15%.

It is observed that sensitivity of turbine loads to ambient turbulence is not constant as TSR is varied. In particular, a larger sensitivity is usually noted at TSR values higher than design point. Standard deviations of measured thrust and power coefficients seem to be more affected by turbulence than the corresponding mean values.

Incoming flow turbulence is expected to increase for turbines operating in the race of other turbines in arrays. Velocity fluctuations are the sum of ambient turbulence and of vortical/turbulent structures that are convected downstream by rotor wakes. The evolution of wakes at model scale implies that diffusion of flow quantities is correctly described and hence Reynolds scaling with respect to full scale is ensured and ambient turbulence levels are comparable to full scale conditions as well. This determines additional difficulties when tests objective is to simulate array conditions. Due to obvious space limitations in confined flow facilities, these types of studies are performed using small size models. In some cases rotor dummies consisting in porous discs are used. Examples of tests with model rotors with rotating blades are limited to 2 -3 rotors, see Mycek et al (2014b).
In addition to onset flow turbulence, the on-site characterization of velocity profiles of marine currents shows the existence of velocity fluctuations occurring at time scales comparable with turbine revolution periods, with relatively high intensity and spatial extension. This can be motivated by large eddies and velocity fluctuations due to surface waves as described above or bathymetry. As an example, ocean waves with periods of 9s may induce axial velocity fluctuations up to 2m/s.

Current speed oscillations are quantified through the so-called current number $\mu$, defined as ratio between the intensity of velocity fluctuation, $u'$ and the mean value of current speed, $U$

$$\mu = \frac{u'}{U}.$$ 

Assuming a mean current speed of 2.0m/s, the example above refers to conditions characterized by a current number close to unity. Under operating conditions with large current number values, large transient blade and hub loads may be generated.

To investigate at model scale the effects of such large-scale velocity fluctuations, towing/flume tanks tests can be performed using special arrangements where oscillating motions are impressed to the model. These motions are combined with a uniform forward speed motion (in towing tanks) or to a uniform onset current (in flume tanks) to yield a fluctuating flow superimposed to a uniform flow.

Oscillatory motions are obtained by means of auxiliary devices like carriages driven by linear electric actuators to impose surge/heave oscillations or fifth wheels for angular motions. For sway and pitch oscillations, Planar Motion Mechanisms (PMM) are also used.

In order to characterize transient loads induced by velocity fluctuations, models have to be instrumented with suitable sensors to measure time histories of thrust and torque at rotor hub. If appropriate, single-blade loads are also recorded. Acquisition rates should be fine enough to make possible the evaluation of frequency spectra through suitable signal processing. Key frequencies to be investigated are 10-15 multiples of flow oscillation frequencies and multiples of turbine blade passing frequency. Solutions to filter background/measuring-chain noise are necessary.

Model tests described e.g., by Whelan (2010) and Milne et al. (2013a) simulated harmonic oscillatory axial motions actuated during model towing at constant speed in calm water. Main objective of tests was to measure turbine blade loads including root bending moments about an axis normal to rotor axis and parallel to blade span. Few examples of multi-frequency oscillation tests are also reported in the literature, see e.g. Milne et al. (2013a).

Transient loads generated on the model by velocity fluctuations require particular care in the set-up to avoid the risk of unstable operating conditions (axial speed and rotor rpm) according to the PTO system modelling procedure. In particular, it should be noted that oscillatory axial motions imposed to a turbine result into heave fluctuations of blade sections. This operating condition may be responsible for dynamic stall and corresponding large overshoots by factors of 2 and more of blade lift and torque with respect to the same blade operating at constant effective angle of attack as in the case of uniform inflow.

### 5.4 Turbine Operation at (Fixed) Yaw Angle

Model tests with the rotor placed at yaw angle with respect to the mean current direction are frequently included in the test matrix to characterise turbine hydrodynamic performance. In this case the yaw angle is kept fixed during measurements. Attention has to be devoted in the set-up to account for loading excess due to lateral inflow velocities at yaw angle.

This type of test can be performed both in towing tanks and in flume tanks/circulating water channels. The model usually represents a simplified sketch of the whole device where only the rotor and a nacelle dummy are present. Typically, the model is fixed to the carriage or supporting frame by a streamlined strut where N-components load cells are fitted.

More complex models including components representing the supporting structure for bottom fixed devices or mooring system for floating or mid-water devices require testing in flume tanks or circulating water channels where
the model is kept fixed against the onset current. In these cases, fluctuating loads on structure components including the rotor are determined by the interaction between the rotor and the supporting/mooring systems.

5.5 REFERENCES


6 MEASURING TURBULENCES UPSTREAM FROM AN FLOATING TIDAL ENERGY CONVERTER

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In the MARINET Transnational Access program a number of companies and research groups have availed of free-of-charge access to European marine renewable energy infrastructures. One of these projects was requested by the German company Schottel. They were allowed to test their STG turbine in the Strangford Lough in Northern Ireland, which position is shown in Figure 1. The administration and supervision of this test site is done by the Queens University in Belfast (QUB).

Figure 1: Test site

The STG turbine is a tidal generator. The rated power is $P_r = 50\text{kW}$ for a nominal current velocity of $v_r = 2.7\text{m/s}$ and the rotor diameter is $d_{\text{rotor}} = 4\text{m}$. For the tests in the Strangford Lough the turbine has been mounted underneath a pontoon. It can be lifted out of the water, so that it is only running when somebody is working on the pontoon. Figure 2 shows a picture and the principle of the turbine setup.

Figure 2: Pontoon
Besides gaining experience about the performance of the turbine under real flow conditions another important part of the tests was to measure flow speeds and turbulences in the surroundings of the turbine. To gather as much information as possible several sensors have been installed and recorded data simultaneously.

During one week a MicroRider from Rockland Scientific (RSI) was installed to evaluate the usability of Rockland Scientific’s velocity shear probe technology to measure small-scale, high-frequency turbulence velocity fluctuations. By combining the results from the MicroRider with those of the Acoustic Doppler Velocimetry (ADV) and the Acoustic Doppler Current Profiler (ADCP) it was possible to investigate flow speeds and turbulences for all scales and frequencies.

The MicroRider is shown in Error! Reference source not found.. It is an internally recording instrument designed to be mounted to an external platform. It is powered by any 12 VDC supply and can be turned On and Off remotely. Shortly after the MicroRider is turned on, it starts data collection and places the information into a new file. Shortly after the instrument is signalled to turn off, it updates a log-file by recording the time and the reason for the termination of data acquisition, then closes all files, and shuts itself down. This makes the instrument well suited to operating autonomously with data collection controlled by a simple ON-OFF signal. Power consumption is approximately 1W when on and 0W when it is off [RSI14].

**MicroRider — Modular Turbulence Module**

![MicroRider](image)

- **Turbulence sensors**
  - Shear Probes (2x)
  - Fast Thermistors (2x)
  - Micro Conductivity (1x)
  - [Micro Fluorometer / OBS]

- **Internal Data Recording**
  - 16 GB memory
  - ~10 kB/s

- **Supply (by platform)**
  - 9 — 18 VDC
  - ~1W
  - Trigger signal [TTL or current input]

- **Outputs**
  - USB data read-out
  - RS-232 for “snippet” data

**Figure 3: MicroRider**

**Figure 4: MicroRider Dimensions**

As shown in the figures the MicroRider can hold up to six sensors. For the measurements in Strangford Lough two Shear Probes and two Fast Thermistors were installed. During the installation of the sensors it is important to check
the set-up of the single sensors. While the Shear Probes should be as close as possible to each other, to assure that the same part of the flow is analyzed, the temperature-sensors should be far away from each other to cover the greatest possible area with the measurement.

The MicroRider must be mounted rigidly below the pontoon with the sensors pointing forward and the principle axis of the MicroRider aligned with the mean flow, which means that the flow has to run through the sensors before it runs around the body of the MicroRider. During the tests the MicroRider was mounted in front of the Turbine at the side of the pontoon, which means that it was not exactly in line with the rotor area. The principle of the setup is shown in Figure 5.

![Figure 5: Sensor Setup](image)

The Vector (ADV) and the Aquadopp (ADCP) were permanently installed at the pontoon. The MicroRider was installed as close as possible to them without interfering with them. Figure 5 was served for the preliminary planning. The main criterion was to keep the MicroRider outside of the wake from the other sensors. Typically the half angle of the wake of a bluff body is approximately 15 degrees, so that the final installation depth was chosen at the test site to approximately 2.3m.

The depth of the centre of the turbine has been 3.5m. It was not possible to install the sensor at the same depth because the installation depth was limited to the length of the mounting pole and its effects on the measurements. As already mentioned the MicroRider was installed to measure small-scale, high-frequency turbulence velocity fluctuations. If a plain round post would have been used to install it, this would have shed eddies and introduced vortex vibrations into the structure. Those vibrations would have contaminated the measurements. So it was important to streamline the post as much as possible to find some other ways to break up the eddies that were streaming off the back side of the strut. To be more specific the mounting pole had to be designed in a way that suppresses vibrations from eddy shedding, particularly those in the frequency range between 1 and 100Hz.
For this reason a tear drop shaped foam profile was attached at the mounting pole with duct tape to streamline the post. Additionally the MicroRider was installed in a tube, which was made from ABS plastic (acrylonitrile butadiene styrene) and filled with rubber couplers to reduce the impact of the vibrations from the pole to the instrument. The tube was a nominal 6 inch plumbing pipe. It was extremely hard, so that it could be drilled to make holes for a bolt-and nut-connection. Figure6 shows the MicroRider with the mounting pole and the holding tube.

Figure6: Micro Rider with mounting pole and holding tube
The tests were performed in different stages. The first day was used to set up and test the MicroRider system dockside. After those initial tests the second day was used to install the MicroRider on the pontoon for short-term tests (1 - 2 hours), to make initial data review and to verify the installation and system health. The other days were used to run long time tests with the length of one tidal cycle, which is 6 hours, in different installation depths. The initial review of the tests showed that the results were better for the lower installation depth which was already termed with 2.3 m.

The raw data of the measurements were afterwards processed by RSI with a special Matlab program. The review of the MicroRider data indicated that they are of high quality and represent a proof of concept of the measurement setup that was deployed. The data sets demonstrate that it was possible to measure the turbulent velocity fluctuations upstream of the Schottel turbine and derive a time series of turbulent dissipation rates in this challenging environment. One example of a time series is shown in Figure.

![Figure 7: Energy dissipation rates for both Shear probes](image)

More information about Rockland Scientific’s velocity shear probe technology can be found in the technical notes from RSI [RSI02], [RSI10] and [RSI13].

### 6.1 References


The following paper, presented at the 2015 IEEE/OES Eleventh Current, Waves and Turbulence Measurement Workshop (CWTM), describes results of the campaign in detail.
Current and Turbulence Measurement with Collocated ADP and Turbulence Profiler Data

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Abstract—This paper presents a current and turbulence measurement campaign conducted at a test site in an energetic tidal channel known as Strangford Narrows, Northern Ireland. The data was collected as part of the MaRINET project funded by the EU under their FP7 framework. It was a collaborative effort between Queen’s University Belfast, SCHOTTEL and Fraunhofer IWES. The site is highly turbulent with a strong shear flow. Longer term measurements of the flow regime were made using a bottom mounted Acoustic Doppler Profiler (ADP). During a specific turbulence measurement campaign, two collocated instruments were used to measure incoming flow characteristics: an ADP (Aquadopp, Nortek) and a turbulence profiler (MicroRider, Rockland Scientific International). The instruments recorded the same incoming flow, so that direct comparisons between the data can be made. In this study the methodology adopted to deploy the instruments is presented. The resulting turbulence measurements using the different types of instrumentation are compared and the usefulness of each instrument for the relevant range of applications is discussed. The paper shows the ranges of the frequency spectra obtained using the different instruments, with the combined measurements providing insight into the structure of the turbulence across a wide range of scales.

I. INTRODUCTION

Energetic tidal sites are of significant interest for their potential tidal stream energy resource. Recent years have seen the development of tidal stream devices for such sites. Tidal stream devices are designed to harness energy from tidal currents, usually converted to electricity, with the available power being proportional to velocity cubed. The predictable nature of tidal hydrodynamics means that the potential power output is highly predictable. However, both hydrodynamic modeling and subsequent validation with site data are required to ensure estimates are accurate. Tidal resource atlases can be very inaccurate [1] as the hydrodynamic conditions can vary considerably over short distances. Furthermore, velocity fluctuations due to friction related turbulence or other obstacles with a wide range of frequencies can contribute significantly to the hydrokinetic energy resource [2]. The influence of these turbulent fluctuations on turbine performance is generally not well understood, which brings into question the applicability of numerical models for determining device performance. Furthermore, while turbulence in general is very well documented [3], literature regarding the turbulent characteristics of high velocity marine currents is by no means extensive, and to date there is relatively little flow measurement data of sufficient detail to properly characterize this type of flow [2], [4]-[6]. Acoustic Doppler Profilers (ADPs) are commonly used to measure flow conditions and can provide turbulence estimates [7]. ADPs, however, often average over too large an area to fully capture the turbulent fluctuations. Consequently, higher resolution and higher frequency methods of measurement should also be used.

The results of the Invest Northern Ireland funded Tandem Tidal Turbine (INI TTT) project, demonstrate the performance differences between Horizontal Axis Tidal Turbines (HATTs) operating in steady uniform flows in a lake environment and in ‘real’ conditions in a tidal channel [8]. In the real flows, significant velocity fluctuations over periods of a few seconds to several minutes were recorded. The ambient turbulence affected the turbines, in terms of power output and performance, leading to decreased single device performance and fluctuations in power output. However, improved wake recovery was observed, thereby indicating that ambient turbulence could result in increased power output when multiple devices interact. While the extent of these effects is specific to exact device characteristics, it was also found in [9], [10] that increasing turbulence intensity can lead to decreased turbine performance, increased power output fluctuations and improved wake recovery. Reference [2] investigates theoretical force and power densities at a tidal site and the authors argue that instantaneous high frequency data should be used to calculate maximum loads for devices until the impact of turbulence on devices is better understood. Furthermore, the fluctuating loads produced by tidal flow turbulence on devices will result in fatigue. Further understanding of the turbulence characteristics of high velocity tidal streams is therefore of importance to device developers and the optimization of the emerging tidal stream sector, to enable more accurate modeling of tidal flows and prediction of device behavior.

The purpose of this paper is to present results of a flow and turbulence measurement campaign conducted using ADPs and a turbulence profiler in an energetic tidal channel. The spectral characteristics of the flow over a wide range of frequencies are determined from the available data set. The limitations of the
current data set are also presented.

II. REVIEW OF INSTRUMENTS AND TECHNIQUES

The most common current measurement instrument used in the tidal energy field is the Acoustic Doppler Profiler. ADPs are used to measure three-dimensional currents throughout the water column using the principle of the ‘Doppler Shift’. Commonly the objective is to obtain time averaged (\( \sim 4 \text{min} \)) estimates of the mean currents. ADPs have been used to obtain estimates of turbulence intensity and can be used for more detailed turbulence characterization. Methods of turbulence analysis are presented for example in [7] and in [11]. One key assumption is that the flow must be homogenous across the spread of the divergent beams. However, the key limitations of ADPs are the spatial and temporal scales that can be resolved and the relatively high levels of noise in the signals. Noise levels in excess of \(0.15 m/s\) have been reported [12], [13].

A review of ocean turbulence micro-structure measurements has been made by [14]. Micro-structure measurements of turbulence in oceans with the use of shear probes have been made since the latter part of the 20th century. The shear probes in the MicroRider provide measurements at a fixed point. The rate of change of the flow is measured by the shear probes and converted to shear of the two orthogonal components to the mean direction. Most studies using turbulence profilers involve campaigns where the profiler is moved vertically through the water. However in this instance, as in [15], the instrument is moored, relying on the movement of the mean current over the profiler [5]. The key advantages of the use of shear probes are the low level of noise, of the order of \(0.001 m/s\) [5], and the high spatial and temporal resolution that can be achieved. However, an independent velocity sensor must be used in conjunction with the shear probes and because the sensing elements are piezo-ceramic beams, fluctuations of lower frequency than \(0.1 \text{ Hz}\) cannot be detected [16].

To date, the use is not widespread in the tidal energy community [16] compared to, for example, the use of Acoustic Doppler Velocimeters (ADVs) for turbulence measurement [4], [17], [18]. An ADV works on the same principle of the ‘Doppler Shift’ as the ADP, but provides higher spatial resolution measurements at a fixed point. Reference [5] provides a detailed comparison of the methodologies and argues that neither ADPs nor ADVs can provide a comprehensive measurement of the turbulence in the water column.

III. METHODOLOGY

In this study a TRDI Workhorse Sentinel ADP was used to measure the longer term flow regime and the available tidal power at the site prior to commissioning of the project. During the specific turbulence measurement campaign an Aquadopp ADP (Nortek) [19] and a MicroRider turbulence profiler (Rockland Scientific International, RSI) were used. The main objective was to obtain a measure of the small-scale, high-frequency turbulent velocity fluctuations. The key focus of this paper is on the two collocated instruments: the ADP (Aquadopp) and the turbulence profiler (MicroRider). While the larger scales of turbulence determine the main part of the turbulent kinetic energy and can be derived from ADP data, the turbulence profiler measurements enable a broader region of the turbulence spectra to be examined. A Nortek Vector ADV was also installed during this campaign but the data is unavailable due to recording errors. The MicroRider can hold up to six sensors. For this campaign two shear probes and two fast thermistors were installed. The temperature sensors are not discussed further in this report. The shear probes are required to be as close as possible to each other, to ensure that the same part of the flow is analyzed. The rate of change of the flow is measured by the shear probes and converted to shear. Due to the orientation of the main body of the MicroRider with the mean direction of the flow (Fig. 1) in this study time series of \(\partial u/\partial x\) and \(\partial v/\partial x\), the two orthogonal components to the mean stream-wise flow direction, were measured. In other studies a Nortek Vector ADV was mounted directly onto the MicroRider to provide mean velocity magnitude measurements. However, in this instance the mean velocity at the installation depth of the MicroRider was measured using the Aquadopp.

A. Mounting of the equipment

During the tests the MicroRider was mounted 2.5 diameters (2.5D) upstream of the turbine on the side of the pontoon, offset by 0.5D from the turbine axis. The instrument setup is shown in Fig. 1. The Aquadopp was mounted immediately upstream of the MicroRider, in order to help ensure the accuracy of the reference mean velocity measurement for the MicroRider. The MicroRider was installed as close as possible to the Aquadopp without interfering with its acoustic beams. The main criterion was to keep the MicroRider outside of the wake of the other sensors. The actual measurement volume investigated in this paper is relatively close to the water surface. This position was primarily chosen to minimize the support structure for both instruments, but also to measure in the upper part of the water column compared to measurements made by [4].

All sensors were mounted on poles clamped to welded brackets on the starboard side of the barge. The Aquadopp and MicroRider were aligned with the principal axis of the barge, which was designed to align with the mean flow direction. The MicroRider sensors were pointing forward, meaning that the flow had to run through the sensors before it encountered the body of the MicroRider.

As the MicroRider was installed to measure the high frequency turbulence, minimizing vibration of the mounting pole was an important consideration. Fairing was necessary in order to suppress vortex shedding from the cylindrical pole. Vibrations in the frequency range between 1 and 100 Hz were of particular concern. Besides vortex shedding of the pole, generator sets or other components on the barge vibrating in these frequency range could cause issues. The fairing was made of foam and designed to give the mounting a foil type profile, being strapped to the mounting pole as shown in Fig. 2. Additionally, the MicroRider was installed in a tube, which
measurements at 2048 Hz and in 2nd and 3rd of July 2014 and the data was collected over periods of approximately 1 hour during one flood tide each day. For the purpose of analysis, records were broken into shorter segments. In this study a sample length of 256 seconds is used. This sample length is comparable to the five minute sample length used in several other studies [4], [18]. Five minutes is considered a suitable sample length for ensuring that the velocity fluctuations are not underestimated, that larger scale fluctuations can be captured and that the time series are stationary, or have stable statistical properties [21]. Wave orbital velocities are assumed to be negligible as the site is sheltered from significant wave action. The data samples under analysis have been extracted from overlapping segments of the time traces from the Aquadopp and MicroRider.

IV. Analysis

The data has been analyzed using a number of routines in Matlab©. In this paper only the velocity spectra from data of the different instruments are being examined. For the turbulence analysis a Cartesian coordinate system is adopted, with the velocity vectors \( u, v \) and \( w \) being the velocities in \( x \) (stream-wise direction), \( y \) (horizontal lateral) and \( z \) (vertical downward positive). The definition of mean velocity will be discussed where relevant.

A. Reynolds Decomposition

The turbulence analysis of the Aquadopp data presented herein is based on the Reynolds decomposition of a short term (stationary [21]) time averaged velocity signal into its mean \( \bar{u} \) and fluctuating, \( u' \) parts. The turbulent fluctuations are the deviations from the mean.

\[
u(t) = \bar{u} + u'(t)
\]  

(1)

A measure of the discrete velocity fluctuations can also be obtained from the shear probe data by integration of the shear signals. However, as previously mentioned, this paper focuses on the spectral, rather than temporal, analysis of the time series data sets to determine a measure of the intensity of the turbulent fluctuations.

B. Spectral Analysis

Spectral analysis of the velocity fluctuations provides information about the density of turbulent kinetic energy across the varying length and time scales of eddies in a turbulent flow.

\[
s_i^2 = \sigma_i^2 = \int_0^\infty E_u(u_i(f) df
\]  

(2)

where \( \sigma_i^2 \) is the variance of the \( i^{th} \) velocity component, \( u_i \), \( E \) is the power spectral density and \( f \) is the frequency.

Shear generated turbulence is formed with the extraction of energy from the mean flow at a low frequency range. This is attributed to large eddies the size of the water depth or the size of boulders, islands and even headlands, as they are shedding in the downstream flow. This range, typically containing the largest part of the turbulent kinetic energy, is hence dependent on the particular physical regime [4] and the shape of the spectrum is expected to be broad peaked. It can be assumed that the size of these large eddies controls the lowest frequency of the turbulence and for example in the case of the test site
with a depth of 15 m and a current speed of 0.8 – 1.5 m/s, a frequency of 0.1 to 0.05 Hz should be expected for the vertical velocity component. At such velocities and with saltwater of around 15°C the depth referred Reynolds number is in the order of \( Re = 1 \times 10^7 - 2 \times 10^7 \), thus flows are clearly fully turbulent. As the larger eddies break down into smaller eddies in a continual process, turbulent kinetic energy is cascaded from the larger to the smaller scales, before eventual dissipation as heat and noise [3]. As should be expected of high Reynolds number flows, an inertial sub-range is observed at a variety of tidal power sites [2], [18], [22]. In the inertial sub-range the turbulence spectrum is proportional to \( f^{-5/3} \). Kolmogorov hypothesized in his Second Similarity Theory that this region is associated with a cascade of energy from larger to smaller eddies, within a certain range of intermediate scales [3]. Furthermore, it is expected that at some stage in this cascade the eddies become isotropic, thus having no predominant orientation of rotation. To obtain information on these eddies the velocity spectrum is being derived from the data. The three dimensional velocity spectra are calculated after removal of the mean of the velocity signals from ADP data, by applying a Fast Fourier Transform algorithm. Spectral analysis of the shear measurements taken by the turbulence profiler yields the shear spectrum. The shear spectrum, \( \Psi_s(\hat{k}) \), can then be used to derive the velocity spectrum, \( \Phi_{ii} \), using the following relationships.

\[
(2\pi\hat{k})^2\Phi_{ii}(\hat{k}) = \Psi_s(\hat{k}) 
\]

\[
\hat{k} = \frac{f}{\bar{u}} 
\]

\[
\Psi_s(\hat{k}) = \bar{u}\Psi_s(f) 
\]

\[
\Phi_{ii}(f) = \frac{\Psi_s(f)}{(2\pi\bar{u})^2} 
\]

where \( \hat{k} \) is the wavenumber in cycles per meter, \( f \) is the frequency, and \( \bar{u} \) is the mean velocity.

V. PROCESSING PROCEDURES

The procedures undertaken during the processing of the raw data through to the to the plotted results are outlined briefly in the following section, regarding quality assurance of the raw data output from the instruments and subsequent post processing.

A. Aquadopp Signal-to-Noise Ratio Thresholds

The signal-to-noise ratio (SNR) indicates the strength of return signals compared to the instrument noise (Doppler noise). As a quality control, unreliable data in this study was identified by having a SNR of \( < 3dB \) based on the guidance by Nortek [19]. SNR values are not output directly by the Aquadopp, but are calculated using the signal amplitude (measured for each ping) and a noise floor of 18 dB. During the measurement campaign the SNR values of the data output by both the barge mounted and bed mounted ADP were high. In bin 7 of the barge mounted ADP, the depth cell corresponding to the depth of the MicroRider, no data points required replacement throughout the range of samples collected. As the bed mounted ADP averaged over each measurement ensemble, individual pings could not be removed. However, the quality of the data was good.

B. MicroRider Processing

During the tests Fraunhofer IWES initially reviewed the data and verified the installation and system health. The raw data of the MicroRider measurements were subsequently processed by RSI. The shear data in the \( \partial v/\partial x \) and \( \partial w/\partial x \) components were provided after band pass filtering, with a high pass cut off of 0.5 Hz and a low pass cut off of 20 Hz. As the principal of potential flow theory is used to measure hydrodynamic lift on the shear probe, the angle of attack of the flow field in relation to the main axis of the MicroRider needs to be derived. The shear probes do not respond linearly to cross-stream fluctuations when this angle exceeds approximately \( \pm 20^\circ \), thus the underlying measurement principle becomes invalid [15], [16]. All samples used in this study had an average angle of attack of \( \leq 10^\circ \). As an initial quality review this has been deemed as suitable, although further analysis on short term fluctuations of the angle of attack may be required. Overall, the review of the MicroRider data during post processing carried out by RSI indicated high quality measurements [23].

C. Spectral Analysis of Time Series Data

A cosine tapered window FFT was used to obtain the spectral energy density distribution from the time series data of flow velocity (Aquadopp) or shear (MicroRider). The data was always conditioned such that there was a \( 2^n \) number of values analyzed, thus ensuring that the data was not re-sampled inside the FFT routine.

VI. RESULTS

The information captured during the testing campaign described in this paper resulted in a large number of processed data sets. A number of the spectral analysis results from the study are presented in the following section. The results from analysis of the longer term monitoring data are followed by the results of the turbulence measurement campaign conducted from the barge.

A. Spectral Analysis of the bed mounted ADP data

Data from one depth cell of the bottom mounted ADP has been extracted for spectral analysis to provide information about the tidal regime at the site. This depth cell is approximately at the same elevation as the barge mounted measurements. The mean magnitude of horizontal velocity over one lunar month at the site was 0.9 m/s and the current flooded with a bearing (coming from) of approximately 120° relative to North. The velocity spectrum generated from this data is shown in Fig. 3. This data was collected and is presented in the East, North, Up (vertical) coordinate system.
There are a number of distinct peaks in all three velocity components. Both East and North velocities are substantially high in terms of energy compared to the vertical velocity. It should be pointed out that the velocities plotted here are the main tidal components and the peaks seen in the spectra relate to the lunar and solar forcing driving the tidal flow. Without going into the details of a harmonic analysis, the M2, N2, S2, and O2 components [24] would be expected to be the main standard harmonic constituents in this tidal record. With periods of 12.42, 12.66, 12.0 and 12.91 hours respectively (which translate to frequencies between 2.15 × 10\(^{-5}\) Hz and 2.31 × 10\(^{-5}\) Hz), these very high energy constituents are closely situated on the frequency plot. The frequencies of the S2 and M2 tidal constituent are indicated by the vertical dashed lines. The spectral analysis performed on this data is in fact not capable of distinguishing clearly between the different components because of the sampling frequency of the data. The main peak in the East and North velocity is also found in the vertical component, though 2 magnitudes smaller in terms of energy. To the left two smaller peaks can be found, probably equivalent to the K1 constituent (1.1 × 10\(^{-5}\) Hz) and some energy not properly resolved equivalent to seasonal components MM and MSF (4.2 × 10\(^{-7}\) and 7.8 × 10\(^{-7}\) Hz). Higher harmonics of the main flow are also observed, equivalent to M3, M4 (indicated on diagram), M5 and M6. Above 10\(^{-4}\) Hz no significant features are evident, though overall the spectral density drops marginally. For reference the inertial sub-range relationship is plotted as a dashed line indicated by its typical slope of \(f^{-5/3}\). It can be seen no part of the observed spectrum follows this line, as would be expected. In fact, what is observed here normally would not be classified as turbulence as even the highest frequency shown is in the order of 5.55 × 10\(^{-4}\) Hz (0.5 hours).

**B. Spectral Analysis of the Barge Mounted ADP Data**

Spectral analysis was performed on the velocity data from the barge mounted ADP. Only depth cell 7 is shown here, which is at the same depth as the turbulence profiler presented in the next section, having its beams less than 0.5 meters upstream. Here the \(u\)–velocity component is aligned with the mean flow, due to the mooring arrangement of the barge.

Samples with a mean velocity greater than 0.8 m/s are used in this analysis. This cut-off has been used in previous studies [4], [25] and is relevant to the cut-in speeds typical of tidal stream devices. The data shown in Fig. 4 is the mean of a large number of velocity spectra, each generated from 256s Aquadopp records. Again it is observed that the \(u\)– and \(v\)–velocity components are very similar, whereas the \(w\)–component is substantially lower (one order of magnitude). All follow a similar trend and do not exhibit any correlation in relation to the inertial sub-range (dashed line with slope \(f^{-5/3}\)). It should be expected that the turbulence starts to decay in terms of energy between 0.1 and 1 Hz (see [18]). This trend cannot be seen here. However, given the relatively high noise floor of the Aquadopp and the lack of homogeneity expected between the different beam velocities, this does not come as a surprise. In fact the spectral curve should flatten out in this range showing the energy of a white noise rather than real turbulence. However, in relation to the operation of a tidal turbine, the magnitude of the turbulence in this frequency range is of particular interest. It can be assumed that in terms of power generation a turbine is capable of reacting to flow fluctuations of the same order of magnitude as its rotational frequency. While this is dependent on the specifics of the turbine (blade configuration, blade profile, drive train inertia and type of generator etc.), this range should be expected in very general terms to be around 0.1 to 1 Hz. Changes in flow at relatively higher frequencies will cause higher loading, but not result in more energy output. Fluctuations at lower frequency will change the torque or rotational speed and thus have a potential to increase power output. Turbulence could, therefore, be distinguished between parasitic and harness-able turbulence.

![Fig. 3. Low frequency range of the East, North and Up velocity spectra from the bottom mounted ADP (key tidal constituents are shown as labeled vertical lines)](image)

![Fig. 4. \(u\), \(v\) and \(w\) velocity spectra from the Aquadopp (AQD) data)](image)

**C. Transition from ADP to MicroRider Spectral Output**

It was anticipated to utilize the MicroRider data in order to determine where the transition from generated turbulence to decaying turbulence lies. In Fig. 5 the \(v\)–components of the velocity spectra from the Aquadopp and the MicroRider data are plotted. As previously mentioned, due to the MicroRider orientation, only the spectra of the \(v\) and \(w\) components can be derived. As would be expected of high Reynolds number flows, an inertial sub-range is apparent from the spectrum generated...
from the MicroRider data, where the slope of the power spectral density is proportional to $f^{-5/3}$. The MicroRider velocity spectrum was calculated using Equation 6. As the shear data used to generate the velocity spectrum was band pass filtered, the regions of the spectrum below 0.5 Hz and above 20 Hz should be ignored in further analysis. As a result, the spectra of the Aquadopp and the Microrider do not overlap.

The translation from shear to velocity spectrum is dependent on mean velocity. In this study the transposition of each sample from shear to velocity has been performed using the mean velocity from the Aquadopp data. The effect of the averaging method used to transpose from shear to velocity spectra was investigated and is shown in Fig. 6. The mean of spectra generated using each sample mean of the quality controlled but unfiltered Aquadopp data and using each sample mean of moving average time traces of the Aquadopp data are both shown. While obviously both follow the turbulence cascade, the latter provides a lower estimate of the turbulent kinetic energy. Considering that the data is plotted on logarithmic scale the energy estimated in the lower trace is $2 \times 10^{-2} \text{m}^2 \text{s}^{-2} \text{Hz}^{-1}$ lower. Ideally a velocity based measurement is also needed, which sufficiently overlaps the MicroRider spectrum to ascertain the correct position of the inertial sub-range.

In the the above figure the MicroRider spectrum has been truncated to the band pass filtered frequencies. However, it can be seen that the $f^{-5/3}$ slope tapers off either end of the band pass frequency range. This may be an effect of the signal filtering used. Similarly, the flattening of the Aquadopp spectra is a result of the spectra becoming saturated with instrument noise, which is assumed to have the properties of white noise. Upon removal of noise from the spectra, the slope of the Aquadopp data would be expected to converge towards that of the MicroRider. However, the lack of the overlap in the frequency ranges of the spectra means that neither assumption can be verified by analysis of the spectra alone in this particular case. From Fig. 4 the anisotropy of the low frequency energy containing range of the turbulence spectra is clear, particularly between the vertical ($w$) and horizontal ($u$ and $v$) components. However, convergence of the three components in the higher frequency range would be expected, consistent with the theory of local isotropy. This has been observed in [18], among other studies.

D. Overlapping ADV and MicroRider Spectral Output

Reference [18] examines ADV data collected from a moored vessel at a location in Strangford Narrows a short distance from the current study site (~100m) in roughly the same water depth and similar mean flow velocities. The velocity spectra results are compared with the spectrum observed in this study in Fig. 7. Both $v$ and $w$ components of the ADV are plotted here to illustrate the non-isotropy below 0.8 Hz followed by a sharp change in the $w$-component to follow the inertial sub-range. The leveling of the ADV spectra, particularly for the horizontal component, away from the $f^{-5/3}$ trend towards higher frequencies, is again indicative of instrument noise in the signals, although lower than the noise in the Aquadopp data. Due to the orientation of the ADV and the fact that the in-axis flow component is correlated from two signals, the vertical velocity component is inherently less noisy than the horizontal components. This explains why the horizontal spectra flatten due to noise at lower frequency than the vertical spectrum [25], [26]. Although not directly comparable in magnitude, the ADV data shown in Fig. 7 overlaps well in frequency range with the MicroRider data. In fact the $w$-component of the ADV is equivalent to the usable frequency range of the MicroRider data in this study.
The aim of the original turbulence measurement campaign under the MaRINET project was to improve knowledge on the effects of small-scale, high-frequency turbulent velocity fluctuations on the performance of a tidal turbine and the resulting mechanical loads [23]. The objective of the bed mounted ADP was to gain data for a resource assessment in accordance with IEC standards [20]. This paper presents the methodology used to measure currents and turbulence at the energetic tidal site. The flow has been measured in order to determine two aspects of the velocity fluctuations, the velocity fluctuation due to the driving forces of the tidal regime and the relatively higher frequency, turbulent fluctuations. The spectral analysis of the flow presents the density of power in each frequency component. Measurements from a number of instruments and obtained using different sampling configurations have been compiled and, in particular, an attempt to obtain a continuous turbulence profile has been made. This paper illustrates the limitations of certain sampling techniques and the overall issue that several instruments are presently needed to produce data that provides overlapping frequency ranges. Ideally a slightly higher sampling rate would have been useful in order to gain a more comprehensive spectral data set. Furthermore, the barge mounted Aquadopp should have collected data at the same sampling frequency, but for slightly longer duration (above 4048 seconds) in order to overlap with the long term ADP data set. The coherence of turbulence analysis could be improved in future measurements if overlap in the spectra of the different instruments is achieved. Ideally, the data used in this study should have been coupled with ADV data from the barge to compliment both the Aquadopp and MicroRider measurements to provide more confidence in the characterization of the turbulence in the frequency range of key interest. Investigations into the characteristics of both large and small scale turbulence and their effect on tidal stream devices are paramount to increase certainty in the design and reduce the cost of this technology. Spectral analysis could prove very important in the progression of the tidal stream industry. Reference [4] suggests that velocity spectra in the frequency domain could be used in conjunction with specific turbine frequency response functions, to provide a method of determining more accurate power estimates, thereby moving away from steady state calculations which are potentially inaccurate. In particular the adoption of a concept, which splits turbulence into parasitic and harnessable components should be developed.

ACKNOWLEDGMENT

The authors would firstly like to thank MaRINET for provision of funding for the project outlined in this study. Thanks in particular also go to the project partners, SCHOTTEL and Fraunhofer IWES, without whom the project would not have been possible. Finally, the authors wish to thank Cuan Marine Services, Applied Renewables Research Ltd. and Rockland Scientific International, for facilitating the project through provision of their expertise and of the measurement platform, data acquisition systems and instrumentation respectively.

REFERENCES


7 WAKE MEASUREMENT OF FULL SCALE TIDAL TURBINES

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The wake of a tidal turbine is of significant interest for device developers. Economic developments will depend on large numbers of devices clustered together in arrays, similar to wind turbines which are commonly installed as wind parks consisting of several devices. The spacing of these devices is a complex optimization problem. Behind each turbine the energy produced by the turbine is missing in the flow downstream and only recovers after a certain distance. The amount of turbines, which can be installed in a certain area and the spacing between these devices, requires careful assessment of this interaction. It is generally accepted that a more turbulent flow environment helps wake recovery but quantifying this effect is complicated. The wake effect is also of interest in environmental assessment studies, since changes in the flow characteristics might affect the natural habitat.

This section describes two attempts to assess the wake of a full scale tidal turbine in field conditions using ADP and ADV measurements.

The tests were performed on the test rig of Queen’s University Belfast behind the Schottel STG tidal turbine, as described in chapter 5.

The following draft document, submitted to the 11th European Wave and Tidal Energy Conference 2015 presents full scale wake measurements, performed during the MaRINET Schottel test campaign.
Abstract—Recent research has shown that higher ambient
turbulence leads to better wake recovery, so turbines could be
installed in closer proximity in 'real' tidal flows than might
be assumed from typical towing tank tests that do not take into
account turbulent inflow conditions. The standard tools to
assess flow velocities in field conditions are Doppler based sonar
devices, such as Acoustic Doppler Profilers (ADPs) or Acoustic
Doppler Velocimeters (ADVs). The use of these devices poses some
challenges when assessing the wake of a tidal turbine. While
ADPs allow the three-dimensional measurement of a velocity
profile over a distance, the data is calculated as a mean of three
diverging beams and with low temporal resolution. ADVs can
measure with higher sampling frequency but only at a single point
in the flow. During the MaRINET testing of the SCHOTTEL
SIT turbine at the QUB tidal test site in Portaferry, Northern
Ireland, ADP and ADV measurements were successfully tested.
Two methods were employed for measuring the wake: firstly, with
a rigidly mounted ADP and secondly, with a submerged ADV
which was streamed behind the turbine. This paper presents the
experimental set-up and results and discusses limitations and
challenges of the two methods used.

Index Terms—wake, tidal-turbine, ADP, ADV, flow-
characterization

I. INTRODUCTION

It is commonly believed, that the tidal industry will only
be able to provide electricity at competitive prices if tid-
al turbines are installed in large arrays, made up of large
numbers of devices. Similar to the wind power industry, the
optimum layout of such a park is of high interest. Optimising
the electricity output for a certain concession area includes
choosing the optimum number of devices and placing them
in the ideal position. A turbine affects the undisturbed
flow at the installation site. The most prominent effect is the
flow deficit behind the turbine, commonly called wake. The
turbine extracts energy in the turbine plane and also induces
tip vortices and turbulence trailing off the blades. The flow
deficit recovers at some distance behind the turbine. Energy
from the ambient flow is distributed by the turbulence and
accelerates the wake. The exact shape and properties of
the wake thus depend for any given turbine design, on the
operating mode, inflow velocity and turbulence levels, water-
depth and bathymetry. For an array developer, the specification
of the wake is crucial. Several numerical optimisation tools for
tidal power arrays have been presented, for example by [1].
Numerical investigations using fully viscous simulation tools
have provided insight into some aspects of wake distribution
and recovery [2]. The importance of ambient turbulence levels
for wake recovery have been demonstrated in experimental
studies on small scale tank tests by [3]. [4] seem to have
performed flow measurements around turbines and compared
them to CFD simulations, but no detailed results are publicly
available. Probably because the industry is relatively young,
no published data has been found by the authors of wake
measurements of actual full scale tidal turbines in real oper-
ating conditions. Full scale field measurements pose several
challenges. The standard tools for flow assessment are by
now sonar devices based on the Doppler effect. Basically two
types of devices exist, Acoustic Doppler Profilers (ADPs) and
Acoustic Doppler Velocimeters (ADV). While ADPs can in
theory provide velocity information over a large spatial range,
the velocity information provided is an average value over
an area spanned by several diverging beams. The temporal
resolution achievable is limited to about 1 Hz. ADVs can
provide high temporal resolution data but only at a single point
in space at any given time. This paper presents the application
of an ADP and ADV for the measurement of the near wake
of the full scale SCHOTTEL SIT turbine during sea trials in
Strangford Lough.

II. ADP MEASUREMENTS

Experiments were performed during the MaRINET testing
campaign in Portaferry, Northern Ireland. The turbine is in-
stalled on a frame hinged to the back of the barge and can be
lifted out of the water, Figure 1. The barge and tidal turbine
have been presented in more detail in [5], [6]. The inflow velocity was measured using an Aquadopp Profiler ADP at the bow of the barge, set to a sampling frequency of 1 Hz and providing data over 10 m with resolution of 0.2 m.

A. Experimental Setup

An ADP is typically used to measure the velocity profile of a current using three or more beams. The Nortek Aquadopp Profiler used for these measurements works with three beams. Each beam is oriented 25° from the sensor head direction. The SCHOTTEL SIT turbine used during the tests had a diameter of 4 m, the wake can be expected to be of roughly the same dimension. The velocity data obtained in standard configuration is calculated from beam data assuming homogeneous flow conditions. About two and a half turbine diameters behind the hub, at 10 m from the sensorhead, each beam spreads to 4.2m = 10m sin(25°) from the centreline, as shown in the sketch in Figure 2. The assumption of homogeneous flow is also not believed to be valid in the wake, rendering multi-beam measurements useless.

However, the main effect of a wake is a velocity deficit in the inflow direction. Using only one beam of the ADP, it is possible to obtain velocity data in beam direction. The ADP was thus installed approximately 0.15 m sideways off the turbine axis, 0.5 m behind the blades. It was oriented so that beam one pointed parallel to the turbine axis into the wake. Installation of the equipment was facilitated by the fact, that the turbine could be lifted out of the water and all installation was carried out on board the barge. Figure 3 shows the ADP attached to the frame, with the turbine lifted.

While ADPs can be configured for autonomous deployment and left to gather data, for these tests the ADP was installed with a cable connection to the barge to enable configuration of different set-ups and external power supply. ADP data was streamed directly onto a notebook. The notebook clock was synchronized with the turbine DAQ at the beginning of the test series. For the results presented in this work, the following configuration was used:

![Fig. 2. Schematic showing the wake of a turbine and the beam spread of a standard ADP application.](image)

![Fig. 3. Photo of the ADP fixed to the support frame, with beam 1 aligned to the turbine axis.](image)

<table>
<thead>
<tr>
<th>Number of bins</th>
<th>45</th>
</tr>
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<td>Bin size</td>
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</tr>
<tr>
<td>Blanking Distanz</td>
<td>0.20m</td>
</tr>
<tr>
<td>Frequency</td>
<td>1Hz</td>
</tr>
<tr>
<td>Head Position below water</td>
<td>3.40m</td>
</tr>
<tr>
<td>Coordinate System</td>
<td>Beam</td>
</tr>
</tbody>
</table>

Measurements were performed between the 23rd August and 16th September. Overall 14 datasets were obtained, typically ranging over a whole test cycle of one outgoing tide. Due to failures during data acquisition only 11 valid datasets were obtained.

B. Processing

The data was downloaded using the AquaPro software provided by Nortek. All further processing was done in MATLAB. ADP Data was discarded when the amplitude count was less than 20. Measurement noise and turbulent fluctuations in the flow were reduced by averaging data over one minute intervals.

Figure 4 shows a sample plot of such a velocity measurement behind the turbine. Velocity seems to increase rapidly within the first two to three bins and then remains relatively constant at around 0.85 m/s. The filtering based on amplitude counts consistently removed any data more than 1.7 diameters downstream of the turbine, limiting the range of the wake assessment to 1.7 turbine diameters.

The inflow velocity to the turbine was derived over various bins according to the industry standard [7] and also averaged in time over one minute. Figure 5 shows the inflow velocity over a complete measurement. The flow velocity follows overall a sinusoidal curve, with a peak around 1.4 m/s after three hours of testing. However the flow is very turbulent, with typical fluctuations of about 0.1% around the local mean. The cut in velocity of the turbine is marked with a horizontal dashed line. Two coloured dots at 1.4 m/s and 0.6 m/s indicate one minute average inflow data that will be used in the following to calculate wake coefficients. If not stated otherwise, data samples averaged over one minute are used for further processing.

With the reference velocity $u_a$ measured at the front of the
barge, the velocity deficit $u_{def}$ is calculated for each position using the formula

$$u_{def} = 1 - \frac{u_{wake}}{u_a}$$  \hspace{1cm} (1)

with $u_{wake}$ being the absolute velocity at the position.

Figure 6 shows the wake obtained for the data shown previously in Figure 5. As expected the wake depends heavily on the operating condition of the turbine. Table I presents key data of the turbine performance for operating conditions 1 and 2.

At point 1 the turbine is spinning with a tip speed ratio of 0.54 and a thrust coefficient of 0.54, indicating the turbine is running in her design load range. In operating condition 2, the turbine has almost come to a standstill and is hardly extracting power, with a tip speed ratio of 1.2 and $c_T$ of 0.21.

For condition one, the wake effect is strongest with values

---

**TABLE I**

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>$c_T$</th>
<th>$\frac{\lambda}{\lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.54</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>0.21</td>
<td>1.2</td>
</tr>
</tbody>
</table>

---

Fig. 1. Sketch showing the barge with the tidal turbine, ADP1 used to measure the inflow velocity at the bow, the ADP beside the turbine and the ADV trailing behind.

Fig. 4. Single beam ADP velocity measurement behind a turbine, averaged over one minute.

Fig. 5. Time trace of inflow velocity, with cut-in velocity of turbine (dashed line) and datasets used for further analysis (coloured dots).
just below 0.6 close to the turbine, dropping quickly and then settling to values of just above 0.4 from 0.4 diameters distance from the turbine.

Operating point two, for the almost stopped turbine, shows a totally different scenario. The wake is almost one at the measurement closest to the turbine and then drops almost linearly with distance to very low levels around 0.1 at 1.7 at the end of the data range.

Fig. 6. Wake coefficient over distance, given in multiples of turbine diameters for various inflow velocities.

III. ADV MEASUREMENTS

The ADV used in this work was a Nortek Vector as shown in Figure 7. The device used can sample with up to 64 Hz, providing much more detailed temporal resolution than an ADP, as was presented in earlier. The biggest challenge in assessing the wake of a tidal turbine is placing the probe in the desired position. The aim of this experiment was to obtain flow velocities at different locations behind the turbine, comparable to the ADP measurements.

A. Experimental Setup

Using many devices in line with the flow might result in disturbances of the flow and is probably not practical due to constraints on the number of available instruments. A fixed structure to hold the probe in place was also not feasible or cost effective. Instead the Vector probe was fixed onto a glider, made up of a 2.5 m steel pole and plywood panels. In the high current environment the panels align the glider well to the flow and keep it close to a horizontal position. Figure 8 shows the glider with the Vector probe and canister attached. For additional safety and retrieving the equipment a red marker buoy was attached with a rope to the back of the glider.

Figure 8 shows the complete set-up being tested close to the surface. The Vector is pointing forward, straight into the undisturbed flow. A rope is attached to the end of the pole. This rope was guided through an eye in the centre of the back of the turbine hub and allowed adjusting the distance between glider and turbine from the barge. Figure 1 shows a sketch of the barge in operation with the glider trailing behind. It should be noted, that the Vector canister contains a pressure sensor sampling with the same frequency as the velocity data and a two dimensional inclinometer sampling with 1 Hz. Due to an error in the set-up no inclinometer data was available. Visual observations during the testing indicate that the glider did not pitch more than 20 deg.

The Vector was deployed to sample at maximum frequency of 64 Hz. The internal clock was synchronised before each deployment to enable comparison and synchronisation with turbine and inflow data, which was again recorded on the main data acquisition system used on the barge.

The glider was deployed by floating it off the back of the barge. The rope was then released and recovered in two 2 m intervals every 5 min, yielding data sets for three positions 1.5 m, 1.5 m+2 m and 1.5 m+4 m behind the turbine. The 2 m

Fig. 7. Photo of the ADV fixed to the glider on the deck of the barge. The probe head is still wrapped in bubble wrap for protection.
distance was marked on the rope with cable ties to improve repeatability.

The distance between measurement points was chosen such that a complete dataset covered a range similar to the ADP measurements while the time between the first and last point in each set (15 min) could still be expected to be in similar inflow conditions.

B. Processing

Data was downloaded using the Vector software provided by Nortek and further processing was done in MATLAB.

The data was split into 5 min chunks relating to each position. A phase-threshold filter as presented by [8] was used to filter the initial vector data. Figure 9 shows a filtered and unfiltered velocity time trace.

The datasets for the three positions measured during one unit[5]min slot were split into one minute packets, similar to the inflow velocity data provided by the ADP at the bow of the barge. Out of the five packets for each position, one was chosen such that the variation of the corresponding inflow velocity was minimised, yielding three datasets, one for each position. Variation of inflow velocity over the three packets was typically less than 5%. A wake measurement thus consists of three points.

The pressure sensor was used to calculate the depth of the glider. Besides the hydrostatic pressure head, corrections were applied for the dynamic pressure, since the pressure transducer was facing into the incoming flow velocity v. The depth D was obtained from the pressure signal p according to the following formula

\[ D = \frac{p - \rho \frac{v^2}{2}}{\rho g} \]  

with g being gravity and \( \rho \) the density of the fluid. Figure 10 shows the depth of the ADV sensor head. The longer the rope, the deeper the glider sinks, indicating that the glider was not neutrally buoyant. 0.4 diameters behind the turbine the glider is 3.6 m below the water level and only about 0.1 m below the ADP beam. 0.8 and 1.2 diameters behind the turbine the glider sinks to 4.1 m and 4.25 m depth. Since the pitch angle \( \phi \) was not measured, no correction is applied. It can be assumed that the sensor head, where the rope was attached, was the highest point. The actual sensor head position is thus rather slightly higher than the data presented in Figure 10.

Figure 11 shows velocities at the three positions behind the turbine for one set of data. Since the pitch angle \( \phi \) was
not measured, velocity data is presented assuming zero pitch angle. Error bars were calculated for ±20 deg pitch. To convert from x and y velocity components $u_x$ and $u_y$ in the ADV frame of reference to horizontal velocity $u$ relative to the turbine, the following relation was used

$$u = u_x \cos(\phi) + u_y \sin(\phi)$$  \hspace{1cm} (3)

The velocity can be seen to be lowest closest to the turbine, while the two points further away are almost on the same level.

Using the inflow velocity, the actual wake is obtained according to equation 1, presented earlier, see Figure 12. The wake effect is strongest, closest to the turbine with a value of 0.65. Less than one diameter downstream from the turbine the wake is only 0.5 and remains almost equal to the measurement at 1.3 diameters distance.

IV. COMPARISON OF ADV AND ADP MEASUREMENTS

Currently no independent measurement of the wake exists, so validation of the methods is limited. Figure 13 shows a wake measured at approximately the same time with both methods. ADP data covers the entire range with a resolution of 0.2 m, while ADV data is only available at three points. Both datasets show high wake coefficients close to the turbine and then only slowly decreasing levels for the remaining range. ADV data is consistently about 20% higher than ADP data, with ADP data lying just outside the error bands.

Besides the low spatial resolution and complex post processing ADV data suffers from another source for potential error. The depth of the glider varies over time and with the distance from the turbine. ADV data is taken up to 0.4 m below the ADP beam, that two data sets are thus not directly comparable.

V. CONCLUSIONS

This paper presented wake measurements performed with a fixed single beam ADP and a ADV attached to an underwater glider in the water column.

A single beam measurement seems suitable to resolve the near wake. It seems feasible to measure longer distances behind the turbine with a different ADP.

The ADV measurements are more complex in post-processing and better methods to ascertain the exact position of the probe might be required. Problems also arise from the relatively long time-scale and limited spatial resolution of the data obtained over the length of the wake. ADV measurements,
with the probe attached to a glider, might though in some cases be the only practically feasible way to access the location of interest. Future applications and further data analysis might also enable the measurement of turbulence levels, which are of very high interest for the validation of numerical tools.

Although no independent data exists for validation of these methods, agreement between the two is satisfactory.

ACKNOWLEDGMENT

The measurement campaign was supported by funding from the FP7 MaRINET program.

REFERENCES


8 INITIAL FLOW CHARACTERISATION UTILISING TURBINE AND SEABED INSTALLED ACOUSTIC SENSOR ARRAYS

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The following draft has been submitted to the EWTEC2015 conference. It presents measurement technology and challenges for device developers resulting from spatial variability of the flow and turbulence.
Initial Flow Characterisation Utilising Turbine and Seabed Installed Acoustic Sensor Arrays

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Abstract—Flow velocity measurements from acoustic sensors mounted both on mid-channel depth tidal turbines and on the seabed are presented for the Fall of Warness in Orkney. The tides are analysed in one hour phases in order to investigate the evolution of metrics over the semi-diurnal cycle. The site is characterised by mean velocity magnitudes and their variation with depth, velocity direction and corresponding variation with depth (twist of the depth profile) and the turbulence intensity and its variation with depth. Analysis shows the maximum velocities of the tides at the site to be within 4° of bi-directionality at a reference ‘point’ 13 m above the turbine with the ebb tide exhibiting greater velocity magnitude as expected from previous site surveys. Variation between the tides is also evident in the twist of the depth profiles which is more pronounced in the lower flood tide, up to a maximum of 7° between the turbine and the surface. In general, both twist of the depth profile and directional variation is greatest at the lowest flow speeds. Mean turbulence intensity is shown to increase near the surface despite no significant drop in the mean velocity, particularly for the ebb tide, indicating wave orbital motion may play a role in near surface fluctuations. Finally a comparison of newly available data from a seabed-deployed ADCP with a Turbine mounted sensor shows a similar velocity depth profile curve but with a mean velocity deficit that is inconsistent over the diurnal cycle. The spatial variation of velocity (and consequent loading) over the rotor plane may prove to be of relevance for device design.

Index Terms—Tidal Energy, Acoustic Doppler Instruments, Site Characterisation

I. INTRODUCTION

The UK’s extractable tidal stream resource is estimated at 116TWh [1] 33% of the UK’s total 354TWh electricity usage in 2012 [2]. However devices are currently conservatively engineered to mitigate a lack of understanding of the environment at high energy sites [3]. In order to be commercially viable, tidal stream energy extraction technology has to be optimised for site specific conditions. Acoustic Doppler Current Profiler (ADCP) surveys are a common method of characterising the flow velocity at potential sites [4]–[9], however a single instrument doesn’t allow the investigations of wider spatial variations of the flow. There are also inherent limitations of ADCP technology, particularly in regard to capturing the turbulent fluctuations of the flow [4], [10], [11].

The ReDAPT (Reliable Data Acquisition Platform for Tidal) project is a UK-based consortium commissioned and funded by the Energy Technology Institute, led by Tidal Generation Limited (TGL) and including Plymouth Marine Laboratory, 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 the EMEC in Orkney, delivering detailed environmental and performance information not previously achieved at this scale in real sea conditions. A central aim of work carried out by the University of Edinburgh in ReDAPT is to measure and characterise the tidal flow surrounding the TGL 1MW turbine at EMECs 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 modelling activities being conducted by project partners.

The variation of flow at mid-channel heights is of interest to turbine developers to predict loads due to variations in principle direction and turbulence across the rotor diameter. Evidence of significant site wide variations would highlight the importance of correct site location for a single device and have consequences to tidal array design and operation.

II. DATA ACQUISITION

The ReDAPT project has thus far completed one preliminary data acquisition campaign, utilising the pre-existing TGL 500kW turbine as the acquisition platform for a suite of seven acoustic sensors between April and May 2012. Initial site characterisation results from this campaign can be found in Sutherland et al [12]. Several additional pre-existing ADCP data surveys in the vicinity of the turbine location are also available for comparison [6]–[9]. In December 2012 an enlarged and improved suite of acoustic sensors was installed on the TGL 1MW turbine which was successfully deployed for commissioning tests in February 2013. The time period over which results have been gathered ranges from the 500kW machine campaign between March and April 2012 to recent data collected between February and March 2013.

For the first deployment of the 1MW turbine seventeen acoustic sensors were installed with an additional ADCP deployed independently on a seabed frame approximately 50m NW of the turbine, aligned with the dominant flood-tide direction. The turbine supports three sets of acoustic instruments: a single Nortek Single Beam Doppler (SBD) velocity sensor on the nose of the turbine, a multi-configurable top frame shown in figure 1 which comprises a Nortek Acoustic Wave and Current Meter (AWAC) and seven SBDS and finally a multi-configurable rear frame comprising four
SBDs along with a long-range Nortek Continental. The standalone ADCP mounted North-West of the turbine is a RDI Workhorse Sentinel. Details of all the instrument hardware can be found in Table I.

Figure 2 indicates the position of the turbine as well as the location of the ADCP surveys within EMEC’s tidal test site. Both the 500kW and 1MW turbines utilise the same foundation platform and operate approximately 25m above the seabed in a section of channel with a mean depth of 43m. The majority of results are presented from analysis captured during the 500kW campaign unless otherwise stated. The methods presented in this paper are being developed for future analysis using the more comprehensive and longer duration 1MW campaign data.

### Table I: Overview of acoustic sensors utilised

<table>
<thead>
<tr>
<th>Name</th>
<th>Sample rate (Hz)</th>
<th>Pulse freq (kHz)</th>
<th>No of beams</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWAC</td>
<td>2</td>
<td>1000</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>SBD</td>
<td>2</td>
<td>1000</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>Continental</td>
<td>1</td>
<td>190</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>RDI Workhorse</td>
<td>2</td>
<td>600</td>
<td>4</td>
<td>50</td>
</tr>
</tbody>
</table>

1. Operational range in deployed configuration

### III. Data Preparation

#### A. Quality control and Period of Stationarity

The quality control procedures are based on instrument manufacturer guidelines [13]–[15] and convention from current literature [4]. Data points with low signal return amplitude or correlation are removed and replaced by cubic interpolation. Segments of data containing greater than 30% ‘bad’ data points are removed altogether.

Instrument random error is assumed to have zero mean and not to affect mean velocity metrics when averaged over a suitably long periods, however it will influence the variance of the measurements and thus turbulence metrics. This is mitigated by a manufacturer supplied noise correction factor discussed further in section IV.

All metrics are calculated over a period of assumed quasi-stationarity of ten minutes. The subject of an appropriate period over which a flow can be considered quasi-stationary is still under discussion, but periods of five to ten minutes are considered acceptable to resolve the relevant scales of motion in the flow while minimising the mean trend gradient over each sample [6]. Unless otherwise stated all data was captured with the turbine reversed to the onset flow, such that the blades are downstream of the measurements to reduce their impact on the measured flow data.

### IV. Site Characterisation Metrics

The ReDAPT measurement campaigns are designed to cover a range of scales of parameters deemed important for site characterisation for the industry [16] of the order of magnitude a single device down to the scales of turbulent fluctuations. This paper focuses on metrics from the larger region of this range of scales.

For much of the analysis velocities are divided into six one-hour long bins about the maximum flow velocity of each tide, hereafter referred to as tidal phases. Figure 3 shows the division of the velocity data into these tidal phases at a reference point 13m above the turbine, gathered by the AWAC during the 500kW campaign. This region of the flow was selected as it was shown to be above that affected by differences in turbine yaw orientation relative to the flow. The TGL turbine is designed such that it can actively yaw to face the onset flow direction of each Flood and Ebb cycle. The same colour key and phase naming convention is used throughout the paper (note the terms waxing and waning
are assumed. Fluctuations equivalent to equation 3 when isotropic velocity fluctuations are available, such as from the SBDs, equation 4 is used. This is achieved with data available from the turbine yaw encoder which is referenced to true North. Throughout this paper $\Theta$ is presented as averaged over an hour (one value per tidal phase) and varies with depth $z$. The resultant direction ($\Theta = 0$) of the flow 13m above the turbine is taken as the reference direction. As this direction is not constant through the depth of the water column a measure of the twist range ($\Delta \Theta$) is defined as the difference between the two most opposed $\Theta$ values as per equation 6. These measurements were taken between 2m and 21m above the turbine. The upper limit is selected to avoid free-surface effects as observed in velocity depth profiles. The effect of the turbine itself on the depth profile requires further investigation.

$\Theta(z) = \tan^{-1} \left( \frac{U(z)}{V(z)} \right) + \alpha \quad (5)$

$\Delta \Theta = \Theta_{Max} - \Theta_{Min} \quad (6)$

V. RESULTS

A. Mean Velocities

The histograms of 10 minute averaged velocities measured by the AWAC from a reference point 13m above the turbine are shown in figure 4. The variation between the ebb and flood tides is evident with the ebb tide showing a consistently higher velocity distribution.

B. Tidal Phase Variation

The directional variation of the tide at a point 13m above the turbine in each phase is illustrated in plan in figure 5. The velocity data across each phase (as illustrated in figure 3) for a given depth are averaged and the resulting variation of flow velocity with depth over each phase is illustrated in figure 6. The flood tide depth profile behaves as would be expected, with boundary layer effects increasing with flow velocity. The ebb tide displays an unexpected reverse in shear direction as it approaches the maximum velocity (light blue line). Although not illustrated, the shear effect of the turbine is much more marked when the sensors are downstream of the operating turbine blades, as would be expected.

Figure 7 shows the direction $\Theta$ (relative to the respective tide’s direction at maximum velocity at the reference height 13m above the turbine) for each phase along with the twist range along the depth profile marked by the whiskers. Figure 7 further illustrates the difference between the ebb and flood tide directional evolution through each of the phases with the flood

\[ I = \frac{\sqrt{u'^2 + v'^2}}{U} \quad (2) \]

\[ I = \frac{\sqrt{u'^2 + v'^2}}{U} - n^2 \quad (3) \]

\[ I = \frac{\sqrt{u'^2 + v'^2}}{U} \quad (4) \]
Fig. 4: Histogram of streamwise velocities

Fig. 5: Tide rose showing variation and velocity direction by phase 13m above the turbine. The flood tide is to the SE and ebb to the NW direction

tide experiencing a greater range of $\Theta$ values as in figure 5. In order to better visualise the twist range, figure 8 illustrates two examples: waxing to and waning from the maximum velocity of the ebb tide, which display a twist range of $6.2^\circ$ and $3.8^\circ$ respectively.

Fig. 6: Mean velocity depth profile by phase

Fig. 7: Mean direction of tide (squares) and maximum twist (whiskers) at each phase across the range 2m to 21m above the turbine
C. Turbulence Metrics

The variation of the mean Turbulence Intensity for each tide with depth is illustrated in figure 9. Both tides produced an increased Turbulence Intensity near the surface with the effect particularly pronounced in the ebb tide. Often an increase in Turbulence Intensity is associated with a corresponding drop in velocity (due to the definition of TI as being divided by the mean velocity) but figure 9 shows that the velocity drop at these depths is not commensurate with the TI increase.

D. Spatial Variation

The most recent data collected during the 1MW campaign between February and March 2013 allows a comparison of cycle again shows disparity between the ebb and flood tides as illustrated in Figure 10. The flood tide has the shallower gradient of the two with the slight increase near the surface as with the mean profile. The ebb tide depth profile shows a more pronounced and less linear increase in TI from the turbine depth to the surface with negligible decrease in velocity. The TI for the slowest phases have been omitted from figure 10 as the metric tends to infinity at flow speeds approaching 0ms\(^{-1}\).
AWAC velocity depth profiles with that of a seabed mounted ADCP 50m upstream of the turbine. Figure 11 shows the difference in mean and phase depth profiles for the two data sets. The two sets of profiles have well matched shear gradients, but display an inconsistent velocity deficit between the two data sets with the AWAC displaying the higher values for five of the six phases by varying quantities. The mean difference between the two mean data sets is 0.05ms⁻¹.

**VI. DISCUSSION**

The results in this paper show tidal metrics vary significantly from ebb to flood tides at the TGL test berth at the Fall of Warness site in agreement with previous analysis [7]–[9]. The characterisation metrics that will be of relevance to device designers are those that will impact upon device loadings and power quality. The two lowest speed phases generally deviate furthest from the mean result for all the metrics analysed; however, they coincide with the velocities below the turbine cut-in velocity of up to 1ms⁻¹ and therefore have reduced relevance to device designers.

The directional analysis presented herein shows that the Fall of Warness site demonstrates a bi-directional tide to within 4° for maximum flow velocities at the reference height 13m above the turbine. This result deviates from previous work which showed a deviation from bi-directionality of approximately 5° in the opposite direction [9]. This previous work calculates direction by averaging over the entire depth where as figure 5 represents a single depth ‘point’ measurement. This highlights the sensitivity of directionality metrics to the averaging length or vertical position selected in a complex flow environment. The flood tide shows an additional spread in angle across the phases with the flow accelerating and decelerating down independent axis separated by angles of up to 30° while still above the cut-in velocity. The available power from the flow lost due to a device being misaligned by a Θ value of 30° is calculated from equation 7 [22], as 25%. This underlines the advantage not only of devices that can yaw, but particularly of those with the ability to yaw during operating conditions.

$$P = \frac{1}{2} C_p \rho A U^3 \cos^2(\Theta)$$  \(_{(7)}\)

The progression of the velocity depth profiles with phase are generally as expected with the exception of the phase approaching maximum speed on the ebb tide, shown in figure 6, which produces a reverse of the gradient against the expected shear. This result coincides with analysis performed on an ADCP survey in a similar location by project partners E.ON [7] which showed at high speeds on the ebb tide a shear reverse in the upper half of the water column (above turbine depth). However in the results presented here, the effect is not consistent over the four highest velocity phases. It is possible that this inconsistency is due to the presence of the turbine disrupting the natural flow pattern and any inconsistency of flow direction could cause a differing effect on the shear. It is interesting to note that work by project partners show that the shear profiles are not consistent over more spatially separated surveys at the Fall of Warness site [7], [9].

The maximum twist of the velocity depth profile is a source of potential loading for devices but the maximum angles measured for the phases of the relevant (> 1ms⁻¹) velocities, although not in a representative portion of the water column, are under 7° (corresponding to a velocity difference of < 0.1ms⁻¹ for highest flow velocities of 3ms⁻¹) and shown to generally reduce with velocity. A notable exception to this is the same phase of the ebb tide that illustrated the reversed shear depth profile.

The increase in TI near the surface illustrated in figures 9 and 10 is likely due to wave orbital motion. Currently the interaction between wave and currents are little understood but is likely to play a part in device loadings, particularly at shallower sites or for near surface devices such as the Scotrenewables device [23]. The TI values are consistently below 10% for the lower portion of the depth profile for velocities of above 1ms⁻¹. This is a lower value than would be expected from similar analysis in Thomson et al [4] for ADCP measurements of TI. The noise correction term (n) used is known to vary with velocity [21] but the effect has yet to be quantified for the range of subsea acoustic sensors utilised for this project and this may account for this lower than expected value.

The comparison of the velocity depth profiles between the seabed mounted ADCP and turbine mounted AWAC data recovered in March 2013 are shown in figure 11. These results only present data for the ADCP 50m upstream of the turbine for the flood tide, due to the turbine orientation during this period of data acquisition. The velocity deficit between the two datasets range up to 0.2ms⁻¹ across a single phase, with a mean of 0.05ms⁻¹ across all phases. The deficit is not equal between phases nor does it decrease with vertical separation from the turbine as might be expected with the additional boundary layer of the turbine. It is worth noting that the shear gradient is similar for both data sets. At a separation of 50m a large disparity between the two data sets would not be expected. The results seen could be due to bathymetrical features across the distance of separation or differences in physical instrument configuration [10]. The effect of increased spatial averaging from the ADCP, due to the greater spread of the diverging beams at the equivalent distance from the seabed, could also introduce a discrepancy between the two data sets. For the bottom mounted instrument, this would incorporate inhomogeneous flow over a wider horizontal plane.

The velocity depth profile of the ADCP in figure 11b illustrates the velocity deficit across a representative blade diameter. The TGL 1MW turbine has a rotor diameter of 18m [24] at a hub height of 25m. This corresponds to vertical extremities of the rotor at 16m and 34m above the seabed. Figure 11b shows a 0.3ms⁻¹ velocity deficit across this range at the highest flow speeds. At a mean flow speed of 3ms⁻¹ this 10% velocity deficit corresponds to a 18% difference in drag force across the rotor plane calculated by equation 8. In reality an equispaced three bladed rotor will never feel this full force
deficit but it underlines the important role that velocity depth profiles could play in blade loadings.

\[ F_d = \frac{1}{2} C_D \rho A U^2 \]  

(8)

VII. FUTURE WORK

With only fourteen days of data currently analysed from the year long 1MW campaign the ReDAPT flow measurement program is still in its infancy. Carrying on from the central theme of this paper a study of spatial variations of site metrics for the sub 100m range is planned with three coincident seabed mounted ADCP campaigns planned for comparison to turbine mounted sensor data. Two ADCPs will be placed approximately 50m either side of the turbine along the principal axis, while a further hard-wired (comms and power) device installed and operated by EMEC is already deployed normal to this axis separated by approximately 95m to the west. These surveys will also allow an investigation into the effect of twist of the flow across the blade diameter and varying direction across the site. A continuing question of interest is the uncertainty of the effects of spatial averaging when using diverging beam acoustic instruments to discern directional and turbulence metrics.

Analysis of turbulence metrics including lengthscales, Reynolds’ stresses and turbulent kinetic energy budget as well as the spectral distribution of turbulent energy across the scales of interest is a key part of the ReDAPT project. Utilisation of the newly available single beam devices in arrays are hoped to capture these parameters more accurately while the long term data measurements will capture any seasonal variation in these parameters.

The effect of waves on measuring turbulence parameters and the potential to separate the two phenomenon in site characterisation measurement work is also to be assessed.

The results in this paper have shown that period of the flow either side of slack water have the highest variation in flow directionality. Although this is out with the turbine operating conditions, the effects on blade and structural loadings at below cut-in conditions maybe under estimated. An investigation to quantify these effects and possible fatigue load impacts at highly energetic sites, where ‘slack water’ is often an erroneous term, could prove to be of value.

Site characterisations are becoming standardised using metrics suggested by work like Gooch et al [16]; however, the central question for site characterisation remains the source of the key drivers for blade loading. In order to do this a large quantity of high frequency and high resolution mean and turbulence data with coincident (or at least statistically representative) blade loading data must be collected for a range of tide and wave conditions. The current maximum instrument sampling rate of 2Hz is a limiting factor in resolving the smaller scales of turbulence. However, the existing instrumentation should allow analysis of the effect of the large scale flow motions on device loadings. The ReDAPT project will have access to blade loading data via strain gauge measurements in order to analyse these relationships. Developing efficient methodologies for accurate site characterisation, including assessment of appropriate instrumentation technology, is an important component of the ReDAPT programme and would find use across the wider industry.

REFERENCES