1 Numerical performance analysis of acoustic Doppler
2 velocity profilers in the wake of an axial-flow marine
3 hydrokinetic turbine

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6 **Abstract**

7 The use of acoustic Doppler current profilers (ADCPs) for the characteri-
8 zation of flow conditions in the vicinity of both experimental and full scale
9 marine hydrokinetic (MHK) turbines is becoming increasingly prevalent.
10 The computation of a three dimensional velocity measurement from diver-
11 gent acoustic beams requires the assumption that the flow conditions are
12 homogeneous among all beams at a particular axial distance from the in-
13 strument.

14 In the near wake of MHK devices, the mean fluid motion is observed
15 to be highly spatially variable as a result of torque generation and energy
16 extraction. We examine the performance of ADCP measurements through
17 modeling of a virtual ADCP (VADCP) instrument in the wake of an MHK
18 turbine resolved using unsteady computational fluid dynamics (CFD). This
19 is achieved by sampling the CFD velocity field at equivalent locations to
20 the sample bins of an ADCP, and performing the coordinate transforma-
21 tion from beam coordinates to instrument coordinates, and finally to global
22 coordinates.

23 The stream-wise velocity deficit and tangential swirl velocity caused by
24 the moving rotor lead to significant misrepresentation of the true flow ve-
25 locity profiles by the VADCP. The most significant errors were observed in
26 the transverse (cross-flow) velocity direction, with a relative error of 17% of
27 the incident velocity. The relative RMS error over the rotor plane was cal-
28 culate to be less than 2% of the incident velocity by a distance of $x/D \geq 2$,
29 $x/D \geq 1$ and $x/D \geq 6$ for the stream-wise, transverse and vertical di-
30 rections, respectively. For the default instrument orientation, A maximum
31 error in the V -velocity occurs when the instrument is located directly be-
32 hind the turbine, and a maximum W -velocity error is found at a lateral
33 offset $y/D = 0.20$. For an instrument directly behind the MHK device, the

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34 maximum error in the U -velocity and V -velocity occurs at a yaw angle of
35 $\phi \approx 30^\circ$ and $\phi \approx 60^\circ$.

36 *Keywords:* Acoustic Doppler Current Profiler (ADCP), Non-homogeneous
37 Velocity, Marine Hydro-kinetic Turbines

38 1. Introduction

39 The characterization of the flow conditions in the vicinity of marine
40 hydrokinetic (MHK) turbines is of importance from the design phase through
41 to the performance monitoring of the operational system. The extraction of
42 energy from such dynamic flow environments is often associated with large
43 changes in the local flow velocity in the vicinity of the device. Such spatial
44 dependence of the flow requires the measurement to be accurate with a
45 relatively high spatial and temporal resolution.

46 Acoustic Doppler current profilers (ADCPs) are often used in situations
47 where simultaneous velocity measurements are desired throughout the water
48 column. This is achieved through the simultaneous sampling of the water
49 column using typically three to five diverging acoustic beams. The ability
50 to configure the acoustic instrument for a wide range of applications has
51 resulted in the broad use of ADCPs in oceans, rivers and estuaries. Other
52 key advantages of ADCPs include the relative ease of deployment and limited
53 post-processing requirements.

54 The operating principle of an ADCP requires the inherent assumption
55 of homogeneity in the flow within the sampled area [1, 2]. Each transducer
56 emits an acoustic signal from the device and processes the reflected signal
57 returned from a range of distances through the water column. The frequency
58 shift from the transmitted acoustic signal is used to calculate the velocity
59 in the direction of the acoustic beam [1]. To calculate a three-dimensional
60 velocity vector, the velocities in at least three non-parallel beam directions
61 must be measured. In order to measure a number of beam directions from
62 a single device, the beam directions are divergent.

63 The reflected acoustic signal is range-gated by the instrument to allow
64 the flow velocity to be sampled at a number of locations throughout the
65 water column [3, 4]. The location corresponding to each gated return signal
66 is referred to as a sample bin. The length of the acoustic beam signal used
67 to calculate the velocity at each sample bin is referred to as the bin length.
68 The flow nearest to the instrument is unable to be measured due a minimum
69 time delay required between each transducer transmitting the acoustic pulse
70 and receiving the reflected signal [4]. The distance to the first sample bin is

Figure 1: Global, instrument, and beam coordinate system notation. The location of bin 5 is highlighted in blue in the left hand figure, and the location of the reference velocity is shown with a black dot. The origin of the global coordinate system is shown in Figure 2. The beam numbering is shown in the x - y plane in the right hand figure.

called the blanking distance. The rate of velocity measurements output by the instrument is referred to as the sampling frequency.

The beam-wise velocities from corresponding bin locations are transformed to calculate a three-dimensional velocity component, notionally located at the same axial distance from the instrument along its central axis, as shown in Figure 1. This process, described in detail in Section 4.1, assumes that the velocity is identical in all the bin locations in a plane perpendicular to the central axis of the instrument. Due to the divergent beam directions, the horizontal distance between bins increases with the distance from the instrument.

While the applicability of ADCPs to measure mean incident flow velocities is well established, the performance of the device in unsteady flows requires a more detailed analysis. This work predominantly involves the comparison of ADCP results with a reference velocimeter or simulation.

85 The primary challenge in verifying the performance of ADCPs in the field
86 is the deployment of a suitable sensor to quantify such a reference velocity.

87 A number of studies have compared ADCP measurements with acoustic
88 Doppler velocimeters (ADV) which measure the velocity at a single point
89 [5, 6, 7]. Of particular relevance to this study, Neary et al. compare the mean
90 velocity measured by a diverging-beam ADCP and an ADV in the wake of an
91 experimental scale horizontal-axis turbine [7]. This comparison highlighted
92 that the non-homogeneous flow of the near wake can lead to significant
93 measurement errors when the homogeneity assumption of a diverging beam
94 instrument is not valid [8]. Nystrom et al. conclude that quantities such
95 as turbulent kinetic energy (TKE), turbulent intensity (TI) and Reynolds
96 stresses can be determined with the ADCPs only after introducing further
97 assumptions to simplify the non-homogeneity of turbulence [9].

98 A virtual ADCP (VADCP) can be modeled to represent the sampling ge-
99 ometry of an ADCP in a representative velocity field. This velocity field can
100 be conveniently generated using computational fluid dynamics (CFD) to re-
101 solve three-dimensional flow effects at a relatively high spatial and temporal
102 resolution.

103 The use of VADCPs to explore the sampling geometry effects is limited
104 in existing literature. Boldt presents the error between the output of a vir-
105 tual ADCP and a number of non-homogenous velocity field cases [10]. These
106 include a range of roller eddy structures and turbulent field measurements.
107 The velocity and Reynolds stresses calculated by a VADCP velocity mea-
108 surements is compared with that calculated from the equivalent locations
109 in a CFD velocity field, using a large eddy simulation (LES) by Tokyay et
110 al. [11]. The modelling of a VADCP is primarily concerned with the ef-
111 fect of the vector transformation from individual beam-wise velocities to a
112 three-dimensional velocity vector. The issue of Doppler noise [12] and other
113 practical operational considerations are ignored.

114 2. Aims and Objectives

115 The numerical simulation presented herein is designed to examine how
116 the flow field in the wake of an axial-flow MHK device risks being misrep-
117 sented by the velocity measurements of a diverging-beam ADCP instrument.
118 A range of instrument locations and orientations are explored to quantify the
119 deviation from the reference velocity as a result of the vector transformation
120 algorithm applied to the diverging acoustic beam geometry.

121 By quantifying the theoretical error caused by the ADCP processing
122 algorithm (in the absence of compounding practical and experimental error

sources), this analysis aims to inform the appropriate deployment proximity and orientation for a range of accuracy requirements and particular flow interests.

3. Simulation of MHK Wake Characteristics

3.1. Introduction to MHK Wake Effects

The primary sources of non-homogeneity in the time-averaged velocity field in the wake of an MHK device can be considered as the superposition of two alterations to the mean flow field:

1. The extraction of energy from the flow by the turbine thrust and support structure drag creates a region of reduced stream-wise velocity behind the device. This velocity deficit is observed in the region known as the ‘far wake’, and is recovered through turbulent mixing with the downstream flow [13].
2. The generation of torque by the operational MHK imparts a reaction ‘swirl’ in the flow close to the rotor plane. This tangential velocity component is a characteristic of the ‘near wake’ and is dissipated by viscous shear forces [13].

A number of theoretical and experimental studies have been conducted to increase the understanding of wake behavior. A tabular summary of a number of these is compiled by Tedds et al. [14]. Data describing information of the behavior of the swirl is limited for the MHK application, even at experimental scale. However studies of this wake characteristic for the application of horizontal axis wind turbines suggest that the wake swirl is dissipated within five diameters downstream of the rotor plane [13].

3.2. Device Geometry

The MHK turbine used in this study is a full scale model of a three-bladed, horizontal axis device on a monopole foundation. The key dimensions of the device and the global coordinate system used throughout the analysis are shown in Figure 2. This turbine was designed using blade element momentum (BEM) theory, and the profiles of the lifting surfaces were determined using the subsonic airfoil design tool ‘XFOIL’ [15]. The development of this device has been a multi-institutional effort involving design at Sandia National Laboratories [16], blade element momentum modelling at UC Davis [15], laboratory testing at Pennsylvania State University [17] and

Figure 2: Coordinate system and geometry of MHK turbine. Dimensions are in meters.

hydraulic and biological performance assessments at the Pacific Northwest National Laboratory [18, 19].

The direction of rotation is in the counter-clockwise direction and the tip speed ratio ($TSR =$) for the simulation was 4. At this operating condition the thrust and power coefficient are equal to $C_T = 0.79$ and $C_P = 0.46$. This operating point represents the peak of the performance curve for the turbine power output.

3.3. Velocity Notation and Coordinate Systems

The coordinate systems and notation used throughout the VADCP analysis is presented below. While other beam numbering conventions exist, the conventions defined in this section are consistent with the VADCP results described and discussed herein.

The beam-wise velocity directions are defined as positive in the direction towards the transducers as shown in Figure 1. The instantaneous beam-wise velocity of beam i is denoted b_i . The two opposing beam pairs are Beam 1 and Beam 2, and Beam 3 and Beam 4.

A Cartesian coordinate system is defined relative to the instrument with directions $[\tilde{x}, \tilde{y}, \tilde{z}]$. This is referred to as the instrument coordinate system. In the following analysis, Beam 2 is aligned in the direction of $\tilde{x}$ and Beam 4 with the $\tilde{y}$ axis. The instantaneous velocity vector aligned with instrument coordinate system is denoted $[\tilde{u}, \tilde{v}, \tilde{w}]$.

178 The global coordinate system, $[x, y, z]$, is defined relative to the compu-
 179 tational domain. This is conveniently aligned with the axes of the MHK
 180 device. The global coordinate system directions and origin are defined in
 181 Figure 2. The instantaneous velocity vectors in this reference system are
 182 denoted $[u, v, w]$.

183 The instantaneous velocity calculated by the vector transformation from
 184 beam-wise velocity vectors to global coordinates are denoted $[u_c, v_c, w_c]$. For
 185 comparison, the instantaneous reference velocity at the same axial distance
 186 from the device, at a point along the central axis of the instrument, are
 187 denoted as $[u_r, v_r, w_r]$.

188 The time-averaged velocity vectors are denoted using the upper-case
 189 notation of the equivalent instantaneous velocity vectors. This mean velocity
 190 is calculated over the entire CFD run duration of 180 s, unless otherwise
 191 stated.

192 The incident flow speed at the turbine hub height is $U_0 = 2.0$ m/s. The
 193 orientation of the beam directions and instrument coordinate systems are
 194 shown within the global coordinate system in Figure 1.

195 3.4. Computational Fluid Dynamics Solution

196 The flow in the wake of the MHK turbine was resolved using an unsteady
 197 CFD simulation of the full-scale device that was previously reported by
 198 Romero-Gomez and Richmond[24]. A detached eddy simulation (DES) with
 199 a $\kappa - \omega$ turbulence solver was implemented using the commercial software
 200 STAR-CCM+ v8 [20] to describe the turbulent flow. The computational
 201 domain of the CFD was $16D \times 8D \times 4D$ (stream-wise, transverse, vertical flow
 202 directions, respectively), where D is the diameter of the swept rotor area.
 203 A hexahedral mesh was used with a total of 10.2M cells. Approximately
 204 30% of these were located in the refined mesh in the vicinity of the rotor
 205 where increased spatial resolution was required for accurate resolution of the
 206 flow behavior about the lifting surfaces. A cylindrical region of the domain
 207 encompassing the rotor was rotated at 3.2 rad/s to simulate the turbine in
 208 operation with a tip speed ratio of 4.0.

209 Field measurements of turbulence were previously examined at an en-
 210 ergetic tidal site, and the turbulent intensity and length scales used in the
 211 present study are derived from that previous work [21]. The inflow velocity
 212 conditions followed a power law with a nominal velocity of $U_0 = 2.0$ m/s, and
 213 contained representative turbulence characteristics of energetic tidal flows
 214 with the turbulence intensity of $TI = 11\%$. The synthetic-eddy-method
 215 presented by Jarrin et al. was used as a well-documented, widely used and
 216 computationally efficient method of generating coherent turbulent eddies in

Figure 3: Instantaneous velocity field upstream of the MHK device and in the near wake, normalized by mean incident velocity of 2.0 m/s [24]

the incident flow [22]. The Lagrangian integral time scale (t_{lag}) was reported to equal 1.4 s. The length scale resulted from multiplying $t_{\text{lag}} \times U_0 = 2.8$ m. This corresponds to the size of the most energetic eddies in the flow. The boundary conditions of the top and side surfaces were modeled as symmetry planes, with no flow recirculation at the outlet plane. The seabed and turbine structure were modeled as no-slip solid walls. Further details on the CFD modeling methods used are reported by Richmond and Romero-Gomez [23, 24]. The resulting incident and near wake flow velocities, normalized by the nominal flow speed of 2.0 m/s are presented in Figure 3.

3.5. Run Duration

The CFD simulation was run for an initial warm-up period of 180 s and then the velocity at the locations corresponding to the bin centers of the VADCP were recorded for an acquisition period of 180 s. The mean velocity components were shown to reach statistically stable values over this acquisition period.

3.6. Velocity Field Characteristics

The velocity field was sampled in vertical planes at $x/D = [1, 2, 3, 4, 6, 10, 12]$ downstream of the rotor plane. The relative magnitude of the wake effects can be considered by normalizing the flow field by U_0 . Recalling the coordinate system defined in Figure 2, selected components of the mean velocity flow field in the x - z plane are shown in Figure 4.

Figure 4: Normalized time-averaged velocity fields in the x - z plane, showing recovery of stream-wise velocity deficit in the wake (top) and transverse component of wake swirl (bottom). The locations of the sample planes are indicated by dashed lines.

The qualitative results demonstrate the characteristic flow phenomena of an MHK turbine wake. In the top plot, a clear region of low stream-wise velocity is observed directly behind the turbine rotor plane with a minimum velocity close to the rotor axis. The wake recovery is observed by the downstream flow mixing to a shear layer with the minimum flow velocity nearest the bottom of the computational domain. The stream-wise velocity deficit in the wake of the rotor is not symmetrical about the rotor axis in the x - z plane. This was observed by Myers and Bahaj [13] in the experimental modeling of a 1/20th scale MHK device and is attributed to the additional velocity deficit caused by the supporting structure between the turbine nacelle and the seabed.

The bottom plot demonstrates the flow swirl as a result of the rotating blades about the y -axis. Tangential velocity components are evident in the transverse direction in the x - z plane as the flow in the near wake rotates about the axis of the turbine rotor. This effect is dissipated more rapidly than the stream-wise velocity deficit, with significantly reduced evidence of swirl at $x/D \geq 5$.

Figure 5: Decay of velocity deficit with distance downstream of rotor plane.

3.7. Validation of CFD Results

The velocity deficit in the stream-wise velocity, U_d , is calculated by Equation 1.

$$U_d = U - U_0 \quad (1)$$

The wake recovery of the CFD velocity field was compared with published results from experimental and computational wake studies of three-bladed MHK turbines in Figure 5.

The wake recovery behaves similarly to that behind horizontal axis wind turbines, where self-similarity exists in the wake [25]. As such, the rate of decay of the stream-wise velocity deficit for each set of experimental results approximates a power law defined by Equation 2.

$$\frac{U_d}{U_0} \approx a(x/D)^{-b} \quad (2)$$

The wake recovery rate, b , was calculated by fitting a power law model to published results in the range $2 < x/D < 12$. The key experimental details and associated wake recovery rates are summarized in Table 1. Direct comparison between each experimental setup is difficult due to the range of experimental methods, geometries, flow conditions, and turbine performance characteristics such as the thrust coefficient, C_T . Yet there are some aspects of the wake behavior that are consistent over all results. A monotonic decrease in velocity deficit is observed in all experiments as well as the

Ref.	Method	D m	U m/s	Re_D -	TI %	TSR -	C_T -	C_P -	b -
[26]	CFD	20	2	4.0×10^7	-	9.2	0.69	-	0.54
[27]	Exp.	0.7	0.8	5.6×10^5	8	-	-	-	0.57
[13]	Exp.	0.8	0.8	6.4×10^5	6	-	0.77	-	0.68
[28]	Exp.	0.27	0.45	1.2×10^5	10	4.7	0.82	-	0.81
[7]	Exp.	0.5	0.4	2.0×10^5	9.8	5.8	0.52	0.48	0.92
[14]	Exp.	0.5	0.89	4.5×10^5	2	6.15	1	0.34	1.04
-	CFD	4.88	2	9.8×10^6	11	4	0.79	0.46	1.08

Table 1: Decay of normalized stream-wise velocity deficit with distance downstream of rotor plane, in order of increasing wake recovery rate. The details of the CFD set-up used in the present study is highlighted in bold.

CFD results. Also, the wake is never observed to have fully recovered by $x/D = 12$.

The theoretical exponent of the wake recovery for the centreline stream-wise velocity of self-similar axi-symmetric wake is $b = 0.66$ [25]. The wake recovery rate of the CFD results used in this analysis ($b = 1.08$) was near the maximum of the range of recovery rates observed in literature ($0.54 \leq b \leq 1.04$). This means that the velocity deficit in the simulated wake of the present study dissipates more rapidly than the majority of other studies. In turn, it can be assumed that the VADCP error values calculated in this analysis are conservative estimates, and would be larger in the more persistent wakes cited in the other studies.

The available quantitative results regarding the expected reduction of the swirl in the near wake is limited. An experimental study of a three-bladed MHK device at experimental scale by Tedds et al. [14] measured a 40-50% reduction in tangential velocity components between $x/D = 1$ and $x/D = 7$. However the turbulence intensity of the flow in these reduced scale experiments was $TI = 2\%$ and so mixing in the wake region can be expected to be significantly less than that in the case modeled in this analysis ($TI = 11\%$). Studies of swirl in the near wake of horizontal axis wind turbines suggest that the tangential velocity component is dissipated within five diameters downstream of the rotor plane [13]. The tangential velocity component was observed to reduce by approximately 75% in the CFD results used in this analysis, between the stream-wise locations of $x/D = 1$ and $x/D = 4$. Again this represents a conservative estimate of the swirl velocity, as the tangential component of the near wake velocity is dissipated at least

298 as rapidly as expected.

299 In addition, the predicted power and thrust coefficients from the CFD
300 model were compared to BEM and laboratory results for these performance
301 coefficients [24, 17]. The results were found to be mostly in agreement in
302 both cases supporting the assumption that the CFD calculation successfully
303 represented realistic flow conditions for use in this analysis. Differences
304 were likely due to the laboratory measurements being done on a reduced
305 scale model in a water tunnel as compared to the CFD simulation for a
306 full-scale turbine in a open domain.

307 4. Virtual Acoustic Doppler Current Profiler model

308 4.1. VADCP Theory

309 The virtual ADCP instrument is modeled by extracting velocity values
310 from the CFD model at locations which correspond to the center of each
311 bin of the four diverging acoustic beams. The velocities at equivalent bin
312 heights directly above the instrument are also recorded as this is the notional
313 position of the velocity measurement. The velocity processing of the VADCP
314 is calculated in the following steps:

- 315 1. The location, blanking distance, bin length, orientation, and sample
316 frequency of the virtual instruments are specified. In the analysis
317 presented herein, the VADCP geometry represents a 4-beam ADCP
318 configuration. The blanking distance is 0.75 m, the bin length is 0.50
319 m and sample frequency of the instrument is 2 Hz. The influence of
320 instrument location and orientation is presented in sensitivity analyses
321 in Section 5.
- 322 2. The velocity vectors are extracted from the unsteady CFD solution at
323 the locations of each bin center of the four diverging acoustic beams.
324 The velocity vectors are also extracted for a vertical acoustic beam
325 with bins at the same axial distance from the instrument, to be used
326 as a reference velocity.
- 327 3. The velocity vectors are converted from Cartesian coordinates into
328 beam-wise velocity vectors. Letting the velocity vector of beam i at
329 bin j be defined as $a_{i,j} = [u_{i,j}, v_{i,j}, w_{i,j}]$ and the unit beam direction
330 vector be denoted as $\hat{d}_i = [\Delta x_i, \Delta y_i, \Delta z_i]$, then the component of the
331 velocity vector in the direction of the acoustic beam is calculated by
332 Equation 3.

$$b_{i,j} = a_{i,j} \cdot \hat{d}_i \quad (3)$$

- 333 4. The beam-wise velocity vectors are combined to calculate a three-
 334 dimensional velocity vector in the instrument coordinate system. Defin-
 335 ing the flow velocity in the direction of beam i as b_i , with positive veloc-
 336 ity being towards the instrument, the coordinate transformation from
 337 beam coordinates to instrument coordinates is given by Equation 4
 338 [11, 3]. The angle of divergence of each acoustic beam from vertical,
 339 which ranges from $20^\circ - 25^\circ$ for most commercial ADCP units, is taken
 340 as $\theta = 20^\circ$ in this analysis.

$$\tilde{u}_i = \frac{b_1 - b_2}{2 \sin \theta} \quad (4a)$$

$$\tilde{v}_i = \frac{b_3 - b_4}{2 \sin \theta} \quad (4b)$$

$$\tilde{w}_i = -\frac{b_1 + b_2 + b_3 + b_4}{4 \cos \theta} \quad (4c)$$

- 341 The coordinate transform from four beams to three Cartesian velocity
 342 components is an over-determined system, and so the mathematical
 343 transformation of Equation 4 is not a unique solution.
 344
 345 5. The velocity vector is transformed from the instrument coordinate
 346 system to the global coordinate system using the roll (ψ), pitch (ϑ)
 347 and yaw (ϕ) angles specified in the ADCP orientation input matrix.
 348 The Euler angle matrix transformation is given in Equation 5.

$$R = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \vartheta & 0 & \sin \vartheta \\ 0 & 1 & 0 \\ -\sin \vartheta & 0 & \cos \vartheta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix} \quad (5)$$

- 349 The relationship between the velocity components in the instrument
 350 coordinate system and those in the global coordinate system is then
 351 given in Equation 6.

$$\begin{bmatrix} u_i \\ v_i \\ w_i \end{bmatrix} = \begin{bmatrix} \tilde{u}_i \\ \tilde{v}_i \\ \tilde{w}_i \end{bmatrix} R \quad (6)$$

- 352 6. The calculated velocity vectors are compared with the co-located CFD
 353 velocity vectors to perform an error analysis. The calculated velocity,
 354 (u_c, v_c, w_c) , is derived using the coordinate transform described in steps
 355 2-5 and compared against the reference velocity at the equivalent axial

Lateral offset (y/D)	Longitudinal distance from of rotor plane (x/D)						
	1	2	3	4	6	8	10
0	✓	✓	✓	✓	✓	✓	✓
0.25	✓	✓	✓	✓			
0.5	✓	✓					

Table 2: Matrix of VADCP instrument locations

distance from the ADCP, (u_r, v_r, w_r) . For every sampled time step, both a calculated and a reference velocity vector are recorded.

7. The mean error as a function of the acquisition time, t_a , is defined for the streamwise direction in Equation 7. This equation is modified for the transverse and vertical velocity error by substituting v and w for the u velocity components, respectively,

$$U_e(t_a) = \frac{1}{t_a} \int_0^{t_a} (u_r(t) - u_c(t)) dt \quad (7)$$

Note that this process models the effect of using four separate beam location to infer a single velocity measurement. The effect of Doppler noise and other known issues associated with field deployments, such as accuracy of positioning and acoustic signal attenuation, have been neglected [21].

4.2. Locations of VADCP instruments

Virtual ADCP instruments were positioned at the combinations of longitudinal and transverse positions are indicated in Table 2.

Point probes are used to extract the unsteady velocity data at 16 Hz from the CFD simulation from the locations of the ADCP bins shown in Figure 6. This data set was down-sampled to 2 Hz as a representative sampling frequency of an ADCP instrument. Additional probes were added upstream of the MHK device to record simulated inflow conditions.

The error between the calculated and reference velocities of the down-sampled 2 Hz data follows a Gaussian distribution over the solution period. The maximum standard deviation of the error velocities is observed in the VADCP instrument measurements closest to the turbine and decreases with wake recovery. The depth averaged standard deviations of the relative error velocities are calculated as 0.37-0.54 m/s, 0.35-0.51 m/s, and 0.16-0.26 m/s for the stream-wise, lateral and vertical flow directions, respectively.

Figure 6: Schematic of probes for VADCP bin center locations. A sub-region of the computational domain is shown for clarity of detail.

4.3. Scaling Effects

The relative locations of the acoustic beams are expected to be similar when an ADCP is modeled in the wake of larger MHK devices. Assuming that the hub height and turbine diameter scale in an approximately linear manner, the ADCP beams will capture similar regions of the flow, as shown in Figure 7. The spatial resolution of the measurements increases for larger MHK devices, with more samples within the rotor plane.

Figure 7: Schematic of ADCP acoustic beams (dashed lines) in the wake of linearly scaled MHK turbine (frontal area of swept blade diameter and monopile support shown in gray).

Figure 8: Comparison of calculated VADCP results and reference flow field velocities from CFD velocity field at $x/D = 2$, $y/D = 0$.

5. CFD Flow Field Results

The results of the calculated VADCP velocity measurements are compared with the reference velocity for the CFD solution for the turbine wake.

5.1. Near wake results

In the default instrument orientation, the stream-wise velocity deficit is qualitatively resolved by the VADCP at the position $(x/D, y/D) = (2, 0)$, however the tangential velocity components introduced by swirl show significant errors, as shown in Figure 8. The maximum relative error magnitude in the transverse flow direction is $V_e/U_0 = 0.17$ near the turbine hub height.

This can be explained by the orientation of the VADCP being aligned with the flow direction. At this orientation, Beam 1 and Beam 2 are in the x - z plane, and Beam 3 and Beam 4 are in the y - z plane. Due to the nature of the wake swirl and the location of the instrument, the V -velocity components observed by Beam 3 and Beam 4 are equal at a particular vertical distance from the instrument. The error is the result of the V -velocity at the beam locations being different from that directly above the instrument where the reference velocity is taken. The reduction in the calculated V -velocity component above the turbine axis is due to the greater separation of the beams at this distance from the instrument. As such, the area of peak swirl in the upper portion of the rotor plane is not able to be captured.

When the VADCP is located at $y/D = 0$, where the actual vertical component of the swirl velocity is zero. With Beam 1 and Beam 2 orientated in the x - z plane at $y/D = 0$, the beams are unable to detect any vertical swirl velocity. As discussed earlier, the beam velocities of Beam 3 and Beam 4 are of equal magnitude and opposite sign. In the numerator of Equation 4c, the

Figure 9: Schematic diagram of beam-wise velocity vectors of VADCP in rotating flow. In the default orientation, Beams 1 and 2 are able to detect the stream-wise flow velocity, U , as well as the vertical velocity component of the swirl velocity, ω_w , when $y/D \neq 0$. Beams 3 and 4 detect both the vertical and transverse components of the swirl velocity.

beam velocities sum to zero. The vector diagram of this scenario is shown in Figure 9.

Due to the inherent difficulties in installing instruments in energetic flows, it is important to examine the cases where the ADCP is not directly downstream of the turbine. The transverse location of one half of the turbine radius is of particular interest as the swirled flow is clearly manifested in both the V -direction and W -direction at this location, as shown in Figure 10. However, the VADCP measurements of the analytical flow field show that neither is resolved correctly by the coordinate transform algorithm. The maximum relative error magnitude in these velocities is $V_e/U_0 = 0.12$ and $W_e/U_0 = 0.04$.

When the ADCP is one radius from the center-line of the nacelle ($y/D = 0.5$), the swirl velocity is significantly reduced. However the calculated velocity incorrectly detects some transverse velocity component with a relative error magnitude of $V_e/U_0 = 0.10$ at the hub height.

5.2. Far wake results

The performance of the VADCP improves with downstream distance from the turbine, as the wake becomes more homogeneous with stream-wise velocity recovery and swirl dissipation. This is observed by the reduction in the RMS error of the normalized velocity components, shown in Figure 11. With a blanking distance of 0.75 m and a bin length of 0.5 m, bin numbers 5-14 are within the vertical range of the rotor plane. Recalling the error

Figure 10: Comparison of calculated VADCP results and reference CFD flow field velocities for three transverse locations at $x/D = 2$.

435 definition of Equation 7, the RMS error for the the stream-wise velocity
 436 over the rotor plane is calculated by Equation 8.

$$U_{e,\text{RMS}} = \sqrt{\sum_{i=5}^{14} (U_{e,i})^2 / 10} \quad (8)$$

437 Figure 11 also indicates the relative significance of the error in the trans-
 438 verse velocity component component for the case where the VADCP is di-
 439 rectly behind the turbine in and aligned with the flow direction ($y/D = 0$,
 440 $\phi = 0^\circ$). The RMS velocity errors for both the stream-wise and vertical
 441 velocity directions are less than 2% of U_0 for $x/D \geq 2$. The RMS error
 442 of the normalized transverse velocity decreases approximately following a
 443 power law reduces to 2% at a location of $x/D \approx 6$.

Figure 11: Mean RMS error of the normalized velocity components over the plane of the turbine rotor, as a function of distance from the rotor ($y/D = 0$, $\phi = 0^\circ$).

6. Analytical Flow Field Results

A simplified representation of the mean flow velocities was implemented in MATLAB to examine the positional sensitivity of the VADCP measurements in the near wake of the MHK turbine in more detail. This flow field was used to approximate the time-averaged CFD simulation results by fitting to the CFD results at $x/D = 2$.

The purpose of developing an analytical flow field solution is so that the mean velocities at all locations in the flow field are readily available and VADCP calculations can be done quickly. To achieve this flexibility using the CFD results becomes computationally expensive since the unsteady velocity field is sampled as the simulation progresses.

The undisturbed longitudinal velocity follows a power law profile. Using the self-similarity law, the velocity deficit in the wake of the turbine is approximated using an exponential profile with a maximum velocity reduction at the hub height [29]. The swirl magnitude is modeled using a Burgers vortex [30]. Both of these models have been used by Hu et al. [31] to model the wake of horizontal axis wind turbines.

The superposition of these wake effects is represented in the analytical flow field defined mathematically by Equation 9.

Figure 12: Development of analytical flow field solution from CFD velocities at $x/D = 2$. The turbine rotor diameter is indicated with a white line.

A	B	C	D	E	F
ms^{-1}	-	ms^{-1}	m	s^{-1}	m
2.2	6	1.4	9.4	0.25	0.68

Table 3: Optimized analytical flow field constants

$$U = A \left(\frac{z + z_T}{z_T} \right)^{1/B} - C e^{-16r^2 \ln(2)/D^2} \quad (9a)$$

$$V = -\frac{EF^2}{r} \left(1 - e^{-r^2/F^2} \right) \left(\frac{z}{r} \right) \quad (9b)$$

$$W = \frac{EF^2}{r} \left(1 - e^{-r^2/F^2} \right) \left(\frac{y}{r} \right) \quad (9c)$$

Here, r is the radial distance from the turbine axis ($r = \sqrt{y^2 + z^2}$) and z_T is the distance of the turbine rotor axis from the tower base. The constants in Equation 9 were determined using a multi-variate optimization using MATLAB to deduce the combination of values which most closely represented the mean CFD results in the range $-1 < y/D < 1$ and $-1 < z/D < 1$. The values calculated from the optimization process are summarized in Table 3. Contour plots showing the velocity deficit in the stream-wise velocity and the affect of swirl on the vertical velocity are shown in Figure 12.

A comparison between the analytical flow field solution and the CFD results at $x/D = 2$ is presented in Figure 13. The velocity deficit in the stream-wise direction show good agreement at all lateral locations, while

Figure 13: Comparison between the analytical flow field solution and the CFD results at different transverse offsets at $x/D = 2$.

the slower tangential velocity components of the analytical solution show less agreement with the CFD. In most cases, the analytical solution underestimates the transverse and vertical velocity components of the wake, however the representative shape of the velocity profiles allows the analytical model to be a useful tool for exploring a range of VADCP orientation and location effects.

The RMS error of relative velocities between the CFD and the analytical flow model can be defined for the stream-wise velocity component by Equation 10, where $N = 19$ for the bin locations within the range of $-1 < z/D < 1$.

$$e_{U_{\text{RMS}}} = 100 \times \sqrt{\sum_{i=1}^N \left(\frac{U_{\text{CFD},j} - U_{\text{Analytical},j}}{U_0} \right)^2 / N} \% \quad (10)$$

A summary of the errors between the CFD solutions and the analytical flow model are presented in Table 4.

A VADCP instrument is modelled in this analytical flow field simulation

	$y/D = 0$	$y/D = 0.25$	$y/D = 0.50$
$e_{U_{\text{RMS}}}(\%)$	1.99	2.75	2.11
$e_{V_{\text{RMS}}}(\%)$	2.14	2.79	2.63
$e_{W_{\text{RMS}}}(\%)$	1.97	3.42	1.67

Table 4: Error analysis for the analytical model of the wake velocity field relative to the CFD solution

in the same manner as in the flow field generated using CFD. The analytical flow model does not include the recovery of the velocity deficit or the dissipation of the tangential velocity (swirl) in the wake of the turbine. This is considered to have a relatively minor effect on the results within the spatial resolution of the VADCP.

6.1. Instrument Orientation Effects

For homogeneous flow conditions, Mueller and Oberg [32] identify that, mathematically, rotating the instrument does not introduce bias in the transformed velocity measurement. However the orientation of the instrument becomes significant in non-homogeneous flow.

To explore the effect of instrument orientation, a VADCP was modeled in the analytical flow field solution to the CFD results at location $x/D = 2$ directly downstream of the MHK device. The VADCP was rotated in yaw in 22.5° increments. A comparison of the calculated and reference velocities is presented in Figure 14. When Beam 1 and Beam 2 are no longer aligned with the flow, measurement errors develop in the calculation of U as well as V .

The sensitivity to the orientation of the instrument is shown in Figure 15. The error between the calculated VADCP result and the reference analytical velocity field is defined by Equation 7. The solution was statistically stable when $t_a = 180$ s.

The observed error is introduced in to the VADCP velocity calculations in two ways:

1. The V -velocity directly above the instrument is different to the V -velocity at the beam locations. This is more pronounced above the turbine hub height where the beams have diverged further.
2. The W -velocity component is non-homogeneous between beam pairs

In the default orientation ($\phi = 0^\circ$), the U -velocity in Beam 1 and Beam 2 are identical and equal to that directly above the instrument (ignoring the

Figure 14: Comparison of calculated VADCP results and reference flow field velocities from the analytical solution to the velocity field at $x/D = 2$, $y/D = 0$.

wake recovery). The U -velocity is therefore quasi-homogeneous in the vertical plane at a particular vertical location. The V -velocity is perpendicular to these beams in this direction and is therefore undetected. The W -velocity component is zero in this plane. The instrument error is therefore zero.

As the instrument is rotated, the V -velocity and W -velocity components are resolved by Beam 1 and Beam 2. The V -velocity at the beam locations is less than that directly above the instrument. Also the W -velocity component is no longer zero and acts in an equal and opposite sense in each beam. This contribution is additive in the calculation of the U -velocity (Equation 4a), and thus an offset is introduced by the W -velocity component. The maximum stream-wise error magnitude of $U_e = 0.20U_0$ occurs at a yaw angle of $\phi \approx 30^\circ$. This is shown in the left hand plot of Figure 15.

For $\phi = 0^\circ$, Beam 3 and Beam 4 are in the vertical plane perpendicular to the mean flow direction. The beam-wise velocity in Beam 3 is equal and in the opposite direction to that in Beam 4 as it would be in homogeneous flow. However, again, the V -velocity magnitude at the bin locations are less

Figure 15: Sensitivity of VADCP results to instrument rotation at $x/D = 2$, $y/D = 0$.

than the V -velocity component directly above the instrument. Furthermore, the offset caused by the non-homogeneous vertical velocity component is present at zero yaw angle. The resulting measurement error of the VADCP is a maximum at an instrument rotation of $\phi \approx 60^\circ$, with the maximum transverse velocity error magnitude of $V_e = 0.28U_0$. This is shown in the central plot of Figure 15.

At the default orientation, the vertical velocity in the vertical plane aligned with the stream-wise flow direction is zero. Beam 1 and Beam 2 velocities are simply detecting the stream-wise flow velocity, and $b_1 = -b_2$ as in homogeneous flow. Similarly, as indicated in Figure 9, the beam-wise velocity components of Beam 3 and Beam 4 have an equal and opposite value such that $b_3 = -b_4$. This observation holds for all orientations of the device. Thus, in the calculation of the W -velocity component, the sum of the beam-wise velocities of both beam pairs is equal to zero, and this explains $W_e = 0$ for all yaw angles at this instrument location.

6.2. Transverse Location Effects

The sensitivity to the transverse position of the instrument is shown by an analysis of the normalized measurement errors as a function of distance from the turbine centerline using the analytical solution to the velocity field in Figure 16.

The VADCP is able to resolve the stream-wise velocity component correctly for all transverse locations. This is because the flow is quasi-homogeneous

Figure 16: Sensitivity of VADCP results to transverse instrument position at $x/D = 2$, $\phi = 0^\circ$.

in the flow direction. That is, in the x - z plane both the U -velocity and W -velocity components do not vary with distance behind the turbine (as the wake recovery and swirl dissipation are not modelled). As such, $b_1 = -b_2$ when $\phi = 0$ for all transverse instrument locations.

The maximum error magnitude in the transverse velocity component of $V_e = 0.14U_0$ occurs when the VADCP instrument is located directly behind the MHK device. As previously discussed, the error is the result of two factors. Firstly, the locations of the acoustic beams are not coincident with the reference measurement location directly above the instrument due to the beam divergence. Both the V -velocity and W -velocity which contribute to the beam velocity of Beam 3 and Beam 4 are different at the location of the acoustic beam to the nominal measurement location. Secondly, as the instrument is moved off-center, the beam-wise velocities are no longer of equal magnitudes, and the difference between the two beam velocities is increased. The local peak of $V_e = 0.07U_0$ at $y/D = 0.58$ represents the transverse offset when Beam 3 intersects the maximum beam-wise velocity component of the swirl (right hand plot in Figure 17). At this offset Beam 4 is located outside of the region of significant swirl.

The error of the vertical velocity component is explained by the summation of the beam-wise velocities of all four beams in Equation 4c. An error is generated when the beam velocities of all four beams are not equal, as they would be in homogeneous flow. It is important to note that because the divergent beam angle is more closely aligned to vertical than horizontal

Figure 17: Normalized velocity components in the y - z plane at $x/D = 2$. Beam 3 (left) and Beam 4 (right) of the VADCP are shown for the case where the instrument is located at $y/D = 0$ with dots, $y/D = 0.20$ with plus symbols and $y/D = 0.58$ with crosses. The turbine rotor diameter is indicated with a white line.

($\theta = 20^\circ$), the vertical velocity component has the greatest influence on the beam-wise velocity.

The peak in the vertical velocity error occurs at the hub height when the instrument is located at $y/D = 0.20$. At this position, Beam 1 and Beam 2 are located in the maximum vertical flow velocity, Beam 3 is close to the minimum vertical velocity in the swirl region Beam 4 is outside of the swirl region ($W = 0$). This case is shown in Figure 17. The vertical velocity measured by the Beam 1 and Beam 2 pair is equal to the reference vertical velocity. However the combined contribution of the Beam 3 and Beam 4 pair is at its minimum. The result is the maximum error of $W_e = 0.03U_0$.

7. Discussion

One of the most common velocity measurements anticipated by an ADCP deployment in an MHK turbine wake is the stream-wise velocity component, which is aligned with the direction of the turbine axis. Both the available flow energy and the largest hydrodynamic forces on downstream arrays of devices are functions of this velocity component. From the VADCP analysis it follows that the theoretical instrument error is minimized when a beam pair is aligned with the flow direction (Figure 15). If this is achieved, then the velocity error is insensitive to lateral instrument location (Figure 16).

However Figure 15 demonstrates that misalignment from this orientation of 30° can cause theoretical velocity errors exceeding 20% of the true

stream-wise velocity at a location of $x/D = 2$ and $y/D = 0$. Such accurate instrument orientation is likely to require active control during deployment such as divers or remotely operated vehicles.

From this analysis the vertical velocity component remains relatively insensitive to instrument location and orientation. This mean velocity component is also typically most accurately resolved by real ADCP instruments, as the beams are more closely aligned with the vertical direction ($\theta < 45^\circ$).

In the configuration explored in this analysis, the additional beam allows a redundant measurement of the vertical velocity. It follows that comparing the vertical velocity calculated using the two beam pairs may provide information about the homogeneity of the instrument. Specifically, the vertical velocity can be calculated as shown in Equation 11.

$$\tilde{w}_1 = \frac{b_1 + b_2}{2 \cos \theta} \quad (11a)$$

$$\tilde{w}_2 = \frac{b_3 + b_4}{2 \cos \theta} \quad (11b)$$

Locations and orientations exist where the two calculated vertical velocities (W_1 and W_2) were very different, but the error between the VADCP velocity and the reference velocity was low. This method of comparing the independent measurements can indeed identify inhomogeneous flows, but does not detect whether such flows are problematic. This is best demonstrated by analyzing the coordinate transform presented in Equation 4c. The four beams velocities are summed in the numerator of the equation. Through this process, a wide range of beam-wise measurements are able to cancel or average out to the true velocity. Thus, while the flow may be quite non-homogeneous, the measurements are able to combine in such a way that zero error is observed.

Similarly, using the beam-wise velocity from all four available beams does not guarantee the maximum accuracy of the measurement. When one beam is located in a region where the velocity is notably different to the others, the measurement error would be reduced by not including that beam-wise velocity in a modification of the coordinate transform. It follows that a sensitivity analysis comparing the performance of VADCPs with three, four and five beams can also be achieved using the VADCP approach. These observations are of interest as the subject of future work using the VADCP model.

The velocity fields used in this analysis are intended to be realistic approximations to those which can be expected behind a full scale MHK device.

634 The CFD model was validated against experiments in literature, and the an-
635 alytical flow field was shown to represent the CFD results at $x/D = 2$. For
636 some full scale devices, this distance is of the order of $x = 40$ m from the
637 device. The magnitudes of the errors identified using the VADCP should
638 serve to raise awareness and provide recommendations for the appropriate
639 use of diverging acoustic Doppler profilers to measure mean velocities in
640 such non-homogeneous flows.

641 From comparison with published experimental results, it was seen that
642 the DES approach used gave rise to higher rates of momentum mixing be-
643 tween the stream flow and the wake flow in comparison to actual field con-
644 ditions. To remedy this overestimated mixing, other formulations such as
645 large eddy simulation could be implemented at a greater computational cost.

646 8. Conclusions

647 The capabilities of an ADCP instrument in non-homogeneous flow in
648 the near wake of a MHK device have been explored through the analy-
649 sis of a virtual ADCP instrument. The velocity field behind an operating
650 three-bladed horizontal axis MHK turbine was resolved using unsteady CFD
651 simulations. The velocity at the locations of the VADCP measurement lo-
652 cations were extracted from the CFD simulation over a period of 180s. The
653 time-averaged stream-wise velocity deficit and tangential swirl components
654 of the near wake were then compared with available literature.

655 The velocity calculated from the beam-wise velocity coordinate trans-
656 form was shown to deviate from a reference flow velocity directly above the
657 instrument in the non-homogeneous wake conditions. The stream-wise ve-
658 locity component (U -velocity) was successfully resolved when the instrument
659 was aligned with the flow. A relative error of $V_e/U_0 = 0.17$ was calculated
660 at the hub height at a distance of $x/D = 2$ due to the tangential velocity
661 component of swirl in the near wake. The relative RMS error over the rotor
662 plane was calculate to be less than 2% by a distance of $x/D \geq 2$, $x/D \geq 1$
663 and $x/D \geq 6$ for the $U_{e,RMS}$, $V_{e,RMS}$, and $W_{e,RMS}$, respectively.

664 In order to efficiently perform a sensitivity analysis on the effect of the
665 orientation and transverse location and rotation of the VADCP, an analytical
666 flow velocity field was developed based on the time-averaged results of the
667 CFD analysis. This analytical solution captured the shear boundary layer
668 and velocity deficit in the stream-wise velocity as well as the swirl effects
669 at $x/D = 2$. For the default instrument orientation, A maximum error in
670 the V -velocity occurs when the instrument is located directly behind the
671 turbine, and a maximum W -velocity error is found at $y/D = 0.20$. For

an instrument directly behind the MHK device, the maximum error in the U -velocity and V -velocity occurs at a yaw angle of $\phi \approx 30^\circ$ and $\phi \approx 60^\circ$, respectively.

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