1 On the near-wall effects induced by an axial-flow rotor

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8 Abstract

9 Laboratory experiments were performed to quantify the near-wall flow char-
10 acteristics and the bed shear stress in the vicinity of an axial-flow rotor model.
11 It was placed in a smooth-wall open channel flow under subcritical conditions
12 and operated at two heights. A laser Doppler velocimeter was used to collect
13 profiles of the streamwise and vertical velocity at few locations within the
14 rotor symmetry plane as close as one wall unit from the bed. Local estimates
15 of the mean bed shear stress were obtained from the mean velocity profiles in
16 the viscous and logarithmic regions. Results show that the bed shear stress
17 is sensitive to the distance from the rotor and to the relative height of the
18 rotor. Maximum bed shear stress occurred downstream of the rotor with the
19 rotor closer to the bed. Flow statistics shows a reduction of turbulence in-
20 tensity and turbulent shear stress near the wall and close to the rotor due to
21 flow acceleration and changes in the pressure distribution. Spectral analysis
22 of the streamwise velocity evidences a reduction of the energy content across
23 scales spanning two decades right below the turbine. The increase of bed
24 shear is due to mainly flow accelerating but not to turbulence.

25 *Keywords:* Bed shear stress, channel flow, hydrokinetic energy, axial-flow
26 turbines

27 1. Introduction

28 Marine and hydrokinetic (MHK) energy conversion has the potential to
29 complement the renewable energy portfolio. MHK concepts are targeted to
30 be deployed in various waterways such as streams, rivers, and tidal currents

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[Drew et al., 2009; Fraenkel, 2002; Gorlov, 2001; Rourke et al., 2010; Khan et al., 2008b]. Recent estimates place the technically recoverable resource at 250 TWh/year for tidal, 163 TWh/year for ocean currents (just from Florida to North Carolina), and 120 TWh/year for undammed rivers [Haas, 2011; Jacobson et al., 2012]. Compared with standard hydropower sources, these concepts are weakly intrusive, leading to reduced effects on the nearby environment and ecosystem [James et al., 2010].

Quantitative characterization of the induced turbulence, its structure and diffusion features, rotor-induced bed shear stress, and its complex interaction with the ambient environment are still subjects of intensive research, not only to achieve optimal MHK turbine operation, but to determine potential environmental impacts and mitigation strategies associated with the relatively emergent technologies [Cada et al., 2007; Khan et al., 2008a; Shields et al., 2009]. Axial-flow turbines can heavily modify the local structure of the flow by generating small-scale turbulence and dampening large-scale motions [Chamorro et al., 2012]. Velocity deficit due to energy conversion from the mean flow can persist far downstream with the wake expansion strongly constrained by the flow bed [Myers et al., 2008]. Rotor wakes are modulated by the dynamics of blade-tip and hub vortices [Felli et al., 2011] and exhibit complex meandering features in the far-wake region [Chamorro et al., 2013; Kang et al., 2014] that appear to be independent of the turbine operation [Okulov et al., 2014].

Onset and dynamics of sediment motions due to increased shear from MHK generators are areas of particular interest due to their effects on water quality, and ecosystem health, among others [James et al., 2010]. Using a 1D morphological model and tidal data of the Bristol Channel in England, Neill et al. [2009] predicted a bed shear stress increase and scour in the region surrounding MHK turbines. Coherent turbulence structures can exert instantaneous drag and lift on the flow bed [Clifford et al., 1993; Diplas et al., 2008; García et al., 1995; Niño and García, 1996; Niño et al., 2003] and numerical simulations by Kang et al. [2012] have shown that the generated turbulence and wake flow can modify the bed shear, which is key for triggering the onset of sediment motion in natural bedforms [García, 2008]. However, Reynolds-averaged boundary shear stresses cannot competently explain the sediment particle movements in the turbulent boundary layer, such as entrainment and transport [Clifford et al., 1993; Diplas et al., 2008], while high-fidelity turbulence measurement in wakes still lacks [Myers and Bahaj, 2010; Chamorro et al., 2013; Neary et al., 2013]. Further, numerical simulations have shown

that turbine arrays have potential impact on the environment, including erosion streams alongside the turbine arrays with deposition in the upstream [Ahmadian and Falconer, 2012], while array configuration with a spacing of five rotor diameters have been proposed to limit excessive hydrodynamic impacts from the MHK turbines [Fallon et al., 2014].

Due to the recognized potential impact of the hydrokinetic turbines on the stability of natural beds, our fundamental study aims to offer insights on the flow structure in the vicinity of bed around a rotor model. Uncovering the flow physics in these situations can provide guidelines toward the general problem of placing hydrokinetic turbines without compromising the natural dynamics of the beds, which is key for the ecosystem and the targeted performance of turbine arrays. For this reason, unique and challenging experiments are designed and performed to characterize the flow features near a fix, smooth bed as close as the viscous sublayer around two rotor setups. To accomplish this, a high-resolution 2-component laser Doppler velocimetry (LDV) was used to obtain flow measurements. The LDV system allows for non-intrusive measurements [Mier and Garcia, 2011] well within the viscous sublayer [Nezu et al., 1997]. The experimental design and measurement procedure are described in Section 2. A quantitative characterization of the flow in the near-wall around the turbine is presented in Section 3 and the main conclusions are discussed in Section 4.

2. Experimental set-up

A three-blade axial-flow type rotor model was placed and operated in a smooth-wall open channel flow under subcritical conditions. The rotor has a diameter $d_T=0.12$ m and its geometry mimics the reference model from Sandia National Laboratory. The cross section of the blades are part of the MHKF1 family of hydrofoils (MHKF1-180s, MHKF1-240s, and MHKF1-400), which is specifically designed for MHK power applications [Shiu et al., 2009]. Figure 1 illustrates a general schematic of the flume and the rotor and the relative location of the rotor within the flume. The turbine blades and nacelle were fabricated with PolyJet Vero photopolymers and 3D printed with an Objet Eden 350 machine with resolution of $50\text{ }\mu\text{m}$. Table 1 summarizes the basic geometry of the turbine blades, which includes the chord length c , and pitch angle α as a function of the radial distance r . The turbine uses Precision Microdrives 112-001 Micro Core 12 mm DC Motor that serves a loading system. Instantaneous voltage from the DC generator was captured

at 5 kHz with a Measurement Computing USB-1608HS DAQ, whose internal
resistance provided the turbine power output.

Figure 1: Schematic of the flume and rotor location (top); and photographs of the flume and schematic the rotor (bottom).

r/R	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95
c/R	0.275	0.248	0.215	0.181	0.156	0.136	0.119	0.100	0.088
α (deg.)	31.8	23.9	17.7	12.8	9.4	7.5	6.0	4.6	3.9

Table 1: Basic geometry of the turbine blades normalized by the rotor radius R : r is the radial distance, c is the chord length, and α is the (pitch) angle with respect to the rotor plane.

The experiments were carried out in the Woods Hole Oceanographic Institute (WHOI) flume at the Ven Te Chow Hydrosystems Laboratory, University of Illinois. The flume is 17 m long, 0.6 m wide, 0.3 m deep, and able to adjust the longitudinal slope. The turbine was placed 13.7 m downstream from the inlet at the center of the flume cross section and under a $H=0.25$ m water depth, providing a blockage ratio ~ 0.08 , and a bulk

113 flow velocity $U \approx 0.28 \text{ ms}^{-1}$, which practically coincided with the veloc-
 114 ity at the turbine hub U_{hub} . The turbine is installed upside down mim-
 115 icking some of the existing structure designs [Lago et al., 2010] and rotor
 116 hub heights z_{hub} were set at $z_{hub}/d_T = 1.04$ (case *a*) and 0.65 (case *b*),
 117 giving submergences $S = (H - z_{hub})/d_T = 1.29$ and 1.68. The resulting
 118 Froude number is $Fr = U/(gH)^{1/2} = 0.18$, where g is the gravity accel-
 119 eration, and the Reynolds numbers, based on the rotor diameter and the
 120 middle-span blade chord length (c_m), are $Re = U_{hub}d_T/\nu \sim 3.1 \times 10^4$ and
 121 $Re = U_{hub}c_m/\nu \sim 4 \times 10^3$, where ν is the kinematic viscosity. A sharp-crested
 122 weir located at the downstream end of the flume controlled the subcritical
 123 flow condition. A turbulent boundary layer of $\delta \approx 0.2 \text{ m}$ thickness and
 124 friction velocity $u_{*0} \approx 0.0118 \text{ m s}^{-1}$ characterized the incoming flow at ~ 4
 125 rotor diameters upstream of the rotor. The turbine operated at constant
 126 tip-speed ratio $\lambda = \pi f_T d_T / U_{hub} \approx 4.0$, where f_T is the turbine frequency
 127 in Hz obtained from video recording and from the power output spectrum
 128 shown in Figure 3, which resulted $f_T = 3 \text{ Hz}$. The spectral distribution of the
 129 power output reveals that the rotor is insensitive to turbulence motions of
 130 reduced frequency $f d_T / U_{hub} \geq 1.2$ or, invoking Taylor’s hypothesis, to length
 131 scales $l \leq 1.2 d_T \sim O(d_T)$. This behavior is consistent with experiments of
 132 Chamorro et al. [2013] with a larger rotor placed in a open channel flow.

133 Laser Doppler velocimetry (LDV) was used to obtain high-resolution and
 134 synchronous measurements of the streamwise (u) and vertical (w) velocity
 135 components of the flow. The LDV system includes a Spectra-Physics Sta-
 136 bilite 2017 Ar-Ion laser, TSI TR 60 Series (3-D, non-submersible) probe, TSI
 137 Model TLN06-363 (363 mm focal distance) lens, TSI Fiberlight Multi-Color
 138 Beam Generator 3-Component optical splitter, TSI PDM1000 photo detector
 139 module, TSI FSA3500/4000 signal processor, Tektronix oscilloscope, and TSI
 140 FlowSizer software. Flow velocity was obtained at few locations along the
 141 symmetry plane of the rotor where emphasis is placed on the very near-wall
 142 region (viscous sublayer). Selected vertical profiles of varied spacing ranging
 143 from $\Delta z = 0.1 \text{ mm}$ to 10 mm and heights (1 mm to 200 mm) were taken at
 144 $x/d_T \sim -4$ (incoming flow), 0 (below the rotor), 0.25, 0.5, 2 and 5. Specific
 145 details of the measurement locations are illustrated in Figure 2. Frequency
 146 sampling varied across the vertical locations due to reduced flow rate in the
 147 near wall region, and ranged from $f = 5 \text{ Hz}$ in the viscous sublayer to 50 Hz
 148 in the logarithmic and outer layers. To allow representative flow statistics,
 149 time sampling varied from 600 s (in the very near wall region) to 240 s in the
 150 outer flow.

Figure 2: General schematic around the rotor and measurement locations.

Figure 3: (a) Spectrum of the power output fluctuations. f_T and f_{bpf} indicate turbine and blade-passing frequencies; characteristics of the incoming flow: (b) streamwise velocity U/u_* , (c) turbulence intensity σ_u/u_* , (d) Reynolds stress $-\overline{u'w'}/u_*^2$.

3. Results and discussion

In this section, we present the flow statistics at the locations illustrated in Figure 2 for the two rotor configurations defined in Section 2. Based on these measurements, we estimate the bed shear around the rotor.

3.1. Mean velocity profiles and bed shear stress

Mean velocity profiles in the viscous sublayer and log layer are used to estimate the mean bed shear stress around the turbine location. The velocity profiles are normalized with inner units i.e., $U^+ = f(z^+)$, where $U^+ = U/u_*$,

159 $z^+ = u_* z / \nu$, $u_* = \sqrt{\tau_w / \rho}$ is the so-called friction velocity, τ_w is bed shear,
 160 ν is the kinematic viscosity and ρ is the fluid density. In the very near wall
 161 region within $z^+ \leq 5$, where the Reynolds stress is negligible, the velocity
 162 distribution over a hydrodynamically smooth wall is described by Equation
 163 1:

$$U^+ = z^+. \quad (1)$$

164 In canonical boundary layer flows, at $z^+ \sim 30 - 300$, the viscous effects are
 165 negligible and the shear stress is approximately constant. The velocity profile
 166 follows a log distribution characterized by:

$$U^+ = \frac{1}{\kappa} \ln(z^+) + C^+, \quad (2)$$

167 where $\kappa \approx 0.41$ is the well-known Von Kármán constant and $C^+ \approx 5.2$
 168 from experimental evidence [Pope, 2000]. The non-dimensional profiles of
 169 the incoming flow ($x/d_T \sim -4$), and right below the turbine ($x/d_T = 0$), as
 170 well as downstream of the turbine ($x/d_T = 0.25, 0.5, 1, 2$, and ~ 5) are
 171 shown in Figure 4 for the rotor located at $z_{hub}/d_T = 1.04$ (case *a*) and at
 172 $z_{hub}/d_T = 0.65$ (case *b*). The velocity distributions from Equations 1 and
 173 2 are included as a reference. The velocity profiles in both cases cover at
 174 least the viscous and log regions. However, the case *a* also includes velocity
 175 profiles of the incoming flow and turbine wake at $x/d_T = 2$ and 5 extending
 176 over the turbine top tip height to highlight the momentum deficit induced by
 177 the rotor and flow recovery with downstream distance [Neary et al., 2013].
 178 Despite the flow behind the turbine is not adjusted, the profiles in both
 179 cases exhibit a self-similar behavior up to the log region, which allowed to
 180 estimate u_* . It is worth mentioning that the extension of the logarithmic
 181 regions is further constrained in the case *b* due to the proximity of the rotor
 182 to the wall and wake expansion. To highlight the collapse of the profiles in
 183 the viscous sublayer, Figure 5 illustrates the velocity distribution for heights
 184 within $y^+ \leq 7$. The linear velocity distribution $U^+ = z^+$ is clearly observed
 185 up to $z^+ \sim 5$, with deviations occurring only over this height.

186 The estimates of the local bed shear stress obtained from the collapse of
 187 the velocity profiles are illustrated in Figure 6 at various locations down-
 188 stream of the model turbine for the two cases. The bed shear stress is
 189 normalized with that of the incoming flow and the distance with the ro-
 190 tor diameter. The figure shows a non-negligible effect of the relative rotor
 191 height z_{hub}/d_T on the magnitude and spatial distribution of u_* . Maximum

Figure 4: Mean velocity profiles normalized with wall units for the turbine rotor located at (a) $z_{hub}/d_T = 1.04$; and (b) $z_{hub}/d_T = 0.65$. Theoretical distributions of the viscous sublayer and log layer are included as a reference in dashed lines.

Figure 5: Mean velocity profiles very near the wall normalized with wall units for the turbine rotor located at (a) $z_{hub}/d_T = 1.04$; and (b) $z_{hub}/d_T = 0.65$. Dotted line shows the $U^+ = z^+$ relationship of the viscous sublayer.

192 u_*/u_{*0} reaches ~ 1.14 and ~ 1.04 (or increase of $\sim 30\%$ and $\sim 8\%$ on the bed
 193 shear stress) for the $z_{hub}/d_T = 1.04$ and $z_{hub}/d_T = 0.65$, while the changes
 194 of u_* extends up to $x/d_T \sim 5$ and 2 , respectively. The case with the rotor
 195 close to the wall ($z_{hub}/d_T = 0.65$) also shows that the maximum bed shear
 196 does not occur right below the rotor but at $x/d_T \sim 0.5$. It probably happens
 197 only at the rotor central plane and is due to the flow acceleration outside
 198 the expanding wake. This downstream shift of the maximum u_* is not ob-
 199 served in the rotor located at $z_{hub}/d_T = 1.04$ probably due to the reduced
 200 flow acceleration. Overall, the $u_* = f(x/d_T, z_{hub}/d_T)$ relationship highlights
 201 the linkage between flow, wall and rotors and the potential onset of sediment
 202 motions when hydrokinetic turbines are placed over beds near critical equi-
 203 librium. In this case, bathymetry can change and substantially modify the
 204 momentum distribution in a river cross section, which can negatively impact
 205 the economy of a hydrokinetic project.

206 3.2. Turbulence statistics and Turbine-induced spectral re-organization of the 207 flow

208 Streamwise turbulence intensity σ_u/u_* and normalized Reynolds stress
 209 $-\overline{u'w'}/u_*^2$ are shown in Figure 7 for the two cases. In the case *a* ($z_{hub}/d_T =$
 210 1.04), the near-wall turbulence statistics in the vicinity of the rotor exhibit
 211 distributions similar to those of canonical flows, where maximum of turbu-
 212 lence levels occur around $z^+ \sim 15$ [Kim et al., 1987; Durbin, 1993]. Within
 213 the rotor wake region, statistics resemble that of the case given by Chamorro

Figure 6: Normalized friction velocity (u_*/u_{*0}) along the turbine axis at $z_{hub} = 1.04$ and $z_{hub} = 0.65$.

et al. [2013] on a similar but larger setup, with deviations at hub and tip vortices while showing no significant change otherwise [Neary et al., 2013]. The similarity features of these statistics appears, however, to break down in the case *b* ($z_{hub}/d_T = 0.65$) and close to the rotor at $x/d_T = 0$ and 0.25 (see Figure 7c,d). It might be due to the local flow acceleration induced by the proximity of the rotor to the bed, leading to changes in the local pressure gradient and consequently departure from the similarity behavior [Fernholz and Warnack, 1998].

The local reduction of the turbulence near the rotor in the case *b* can be further inspected by comparing the structural distribution of the turbulence with that of the incoming flow. Figure 8 illustrates the pre-multiplied spectra, $f\Phi$, of the streamwise velocity of the incoming flow, included as a reference and wake at $x/d_T = 0$ and $x/d_T = 0.25$ at $z^+ = 10$ and $z^+ = 12$ for the case *b*. This figure shows that the energy content of the organized turbulence motions is dampened across all the scales resolved. In particular, the large-scale motions, populating the incoming flow and characterizing the near wall region turbulence [Hutchins and Marusic, 2007; Balakumar and Adrian, 2007; Guala et al., 2011], are dampened below the rotor bottom tip. To better illustrate these differences at various heights, 2D pre-multiplied spectral difference ($\Delta f\Phi_u$) between the incoming flow and $x/d_T = 0, 0.25$ and 2 (case *b*) near the wall ($z^+ < 60$) is shown in Figure 9. It suggests that the spectral energy content is mostly dampened within heights below the buffer

Figure 7: Streamwise turbulence intensity σ_u/u_* . Symbols $\circ$, incoming flow; $+$, $x/d_T=0$; $*$, $x/d_T=0.25$; $\times$, $x/d_T=1$; $\triangle$, $x/d_T=2$; $\square$, $x/d_T=5$.

236 layer and contained within a frequency band extending roughly two decades.
 237 The energy content reduction is the highest right below the rotor, which ap-
 238 pears to reduce rapidly with downstream distance to practically recover the
 239 features of the incoming flow at $x/d_T \sim 2$. These results further suggests
 240 that the enhanced shear at the wall (14% increase in u_* or $\sim 30\%$ of τ_w) is
 241 mainly due to local flow acceleration, not to turbulence.

Figure 8: Pre-multiplied power spectra ($f\Phi$) of the incoming flow, at $x/d_T=0$, and at $x/d_T=0.25$ with $z_{hub}/d_T = 0.65$ hub height setting: (a) $z^+ = 10$; and (b) $z^+ = 12$.

Figure 9: 2D pre-multiplied spectral difference ($\Delta f\Phi_u$) between the incoming flow and that at (a) $x/d_T=0$, (b) $x/d_T=0.25$, and (c) $x/d_T=2$. $z_{hub}/d_T = 0.65$ case.

242 4. Conclusions

243 Detailed characterization of the flow velocity in the vicinity of a rotor
 244 model, including the viscous sublayer, allowed the estimation of the bed shear
 245 stress distribution at various locations along the axis of the rotor placed in
 246 an open channel flow under subcritical conditions. Results show that the
 247 bed shear stress is very sensitive to the distance from the rotor and to the
 248 relative height of the rotor z_{hub}/d_T . Specifically, bed shear slightly changed
 249 with the rotor located at $z_{hub}/d_T \sim 1$; however, an increase of 30% occurred
 250 with the rotor at $z_{hub}/d_T = 0.65$. Turbulence level is comparatively lower in
 251 regions of increased bed shear, suggesting that the likelihood of particulate
 252 motion in beds is due to flow acceleration. Comparison of the spectral content
 253 of the flow turbulence below the rotor and that of the incoming flow shows
 254 a damping of the turbulent energy across scales spanning two decades. It

255 indicates that the flow/bed dynamics near hydrokinetic turbines is dominated
256 by small-scale turbulence. This study provides insights for assessing potential
257 erosion near the turbine based on local bed sediments and turbine proximity
258 to bed. Subsequent work will consider near wall characterization of the flow
259 under multiple rotor scenarios with various tip-speed ratios. To the best
260 knowledge of authors, these type of measurements around rotating rotors
261 have not been performed experimentally.

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