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Observations of Turbulence in a Strong Tidal Flow

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Abstract

Compared to the atmospheric boundary layer, there exists a lack of observations of turbulence in strong tidal flows. Such data are of increasing interest for charactering the dynamic loads on tidal turbines and validating numerical models. To this end, we report on a set of turbulence measurements acquired at the Sound of Islay in Scotland. The measurement location corresponds approximately to the site of a proposed tidal turbine deployment. The tidal channel is relatively deep at around 60 m, has sedate surface waves and the mean tidal flow exceeds $2.5\,\mathrm{m\,s^{-1}}$. An experiment set-up comprising an ADCP and ADV deployed on the seabed was utilised to measure statistics such as the turbulence intensities, Reynolds stresses and spectra over the tidal cycle. These measurements were used to inform the turbulence structure and dominant length-scales in the water column. The properties were found to be generally consistent with empirical correlations devised for steady open-channel flows in the laboratory and other field measurements reported on in the literature. It is envisaged that these results will aid designers of tidal turbines in reducing the uncertainties associated with the hydrodynamic loading on tidal turbines.

Introduction

In comparison to the atmospheric boundary layer, there remains a lack of observations of turbulence in highly energetic tidal flows reported in the literature. Observations of turbulence at elevations beyond the immediate region above the seabed and throughout the water column are particularly scarce. This can be attributed, in part, to the inherent technical difficulty in acquiring measurements in strong flows [15]. Recent reports of tidal turbine failures have however emphasised the need for such data to assist in quantifying the unsteady loading on tidal turbines [12].

The pioneering studies of observations of turbulence in tidal channels (e.g. [5, 2, 8, 16, 7]) were typically derived from electrocurrent meters. These works provided support for universal laws based on surface similarity theory and the hypotheses of Kolmogorov [9] to describe the distributions of the turbulence scales. The study by [8] specifically provided anisotropic ratios and also described the intermittent nature of the Reynolds stress. However, the vast majority of the studies reported in the literature have been based on relatively slow and shallow flows. Furthermore, the turbulence was generally investigated at elevations very close to the bed as sediment transport was of primary interest.

Advances in sensor technology and the introduction of acoustic-Doppler current profilers (ADCPs) and velocimeters (ADVs) in particular has enabled turbulence to be measured relatively unobtrusively at greater elevations above the seabed. The application of ADCPs and ADVs to the analyses of tidal flows specifically are reviewed by [1]. Experiments which employ these sensors have the potential to provide new insights into the turbulence structure and dominant scales at elevations more aligned with the interests of the tidal energy industry.

We report here on a series of measurements acquired using both an ADV and ADCP at the Sound of Islay in the Inner Hebrides of Scotland. The intention of the study was to provide new observations which could be used to assess the applicability of universal scaling laws and empirically derived correlations of open-channel flows for strong tidal flows. The site was selected on the basis that it is subjected to tidal currents with mean velocities exceeding $2.5\,\mathrm{m\,s^{-1}}$, has a simple geometry, weak levels of freshwater input and sedate wave action. As such, it was considered that the hydrodynamic conditions would be most aligned with that of a two-dimensional open channel flow. This study extends the work of Milne et al. [13] by including distributions of the mean flow through the water column and specifically characterising the Reynolds stresses and its relation to the turbulence intensity.

Experimental Methodology

Description of the Site

The present observations were made in the central section of the Sound of Islay, which is a tidal channel approximately 30 km in length flowing nearly North to South between the Isles of Islay and Jura in Scotland. At the location that the measurements were obtained the channel width and depth is around 800 m and 55 m, respectively. The topography of both Isles is such that the channel is sheltered from significant wind induced waves. The acquisition site corresponds approximately with the location of a proposed tidal turbine array. As detailed by [12], the topography of the site is characterised by a seabed that falls steeply from the shore. The seabed comprises boulders, rock and gravel, with little fine sediment.

Data Acquisition & Analysis Techniques

The data were acquired using a set-up comprising both an ADCP and an ADV which were positioned within close proximity on a steel frame that was deployed on the seabed. The TRDI 1.2 MHz Workhorse ADCP was configured to continuously record the velocities in a direction aligned with the beams of the sensors. The four diverging beams were inclined at an angle of $\theta = 20^\circ$ from the vertical and were arranged in a Janus configuration (i.e. at 90° azimuths about the vertical axis). The measurements were acquired at a sampling frequency of 2 Hz and at 1 m vertical intervals, with the lowest recordings at $z = 4$ m above the seabed.

The ACDP data were used to inform the distributions of the mean velocities and the Reynolds stresses through the water column. Due to the assumption that the turbulent flow was non-homogeneous across the lateral spacing of the beams (which was of the order of 10 m at mid-depth), the instantaneous Cartesian velocities could not be reliably measured by the ADCP. The Reynolds stresses (considered hereafter in terms of the velocity covariances) were estimated by employing the variance technique demonstrated by [10]. Using this approach the along-channel stresses were obtained to the first order from the expression

$$-\sigma_{uw} = \frac{\sigma_{b2}^2 - \sigma_{b1}^2}{2\cos 2\theta}, \quad (1)$$

where b_i is the fluctuating velocity measured along the direction of the i^{th} beam. This approach inherently assumes that the second-order moments are statistically homogenous across the lateral separation of the beams and the sensor tilt is small. For the present study, the relatively small tilt angles of the sensor were considered to result in an error of around 10 % in the stresses [12].

A Nortek Vector ADV was deployed to measure all three fluctuating velocities at a fixed point above the seabed. The ADV was mounted in an upright configuration at the top of a steel mast which was affixed to the base frame. The ADV measurements corresponded to an elevation of 5 m above the seabed. The ADV had a sampling volume of 14 cm^3 and sampled the velocities at a frequency of 4 Hz continuously over the duration of the experiment. The vector measurements were acquired in beam coordinates (i.e. aligned with the transducers of the sensors). The velocities u, v and w were obtained by first transforming the raw measurements to a Cartesian coordinate system aligned with sensor and subsequently, to an Earth-fixed system which accounted for the sensor tilt. Finally, the horizontal velocities were transformed such that the streamwise and lateral velocities aligned with the mean velocity direction for each sample. Further details on the processing of the ADCP and ADV measurements as well as the quality control measures that were employed are provided by [12].

Results and Discussion

Tidal Regime

The measurements were acquired over a 29-day period in November 2009. Time histories of the mean velocity and water elevation over the complete experiment have been previously reported by [12]. These showed that the flow within the channel was asymmetric with stronger currents generally observed on the Southerly ebb. The highest tidal velocities of around 2.5 $m s^{-1}$ were observed during spring tide, while the peak velocities at the neap were around 1.5 $m s^{-1}$. The directionality of the flow was near-uniform through the water column and flow was assumed to be well mixed due to the high flow speeds and little freshwater input. The surface waves were small with significant wave heights generally less than 1 m. The water level variation over the spring tidal cycle was also relatively small at around 1 m. The strong currents arise due to the difference in the tidal phase around the Isles and are influenced to a comparatively small degree by the tidal range. The investigations reported on here are focused on the observations during the spring tidal cycle. These observations of the mean flow and the turbulence properties were found to be generally representative of that which was observed for several tidal cycles around the spring tide.

Through Water-Column Profiles of Mean Velocity and Stresses

The evolution of the boundary layer over the spring tide is by the mean velocity profiles figure 1, which indicate a rapid development from slack flow. The thickness of the boundary layer (considered to correspond to the elevation where U = 99 percent of the maximum velocity) was at least 50 m during the peak flood flow and reached a maximum of around 40 m during the ebb. In general, there were no indications in the profiles that strong secondary subsurface currents were present.

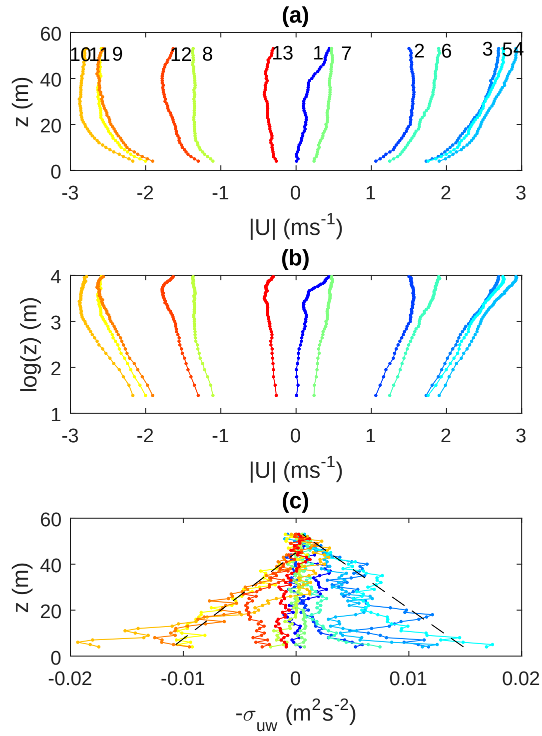

Figure 1: Profiles of the mean velocity and Reynolds shear stress observed at consecutive hourly intervals during the spring tide (labelled for reference). The profiles for the ebb tide are denoted as negative for clarity and a linear fit to profiles 5 and 9 is shown for comparison with the theoretical prediction.

The finding that the boundary occupied the majority of the water column is consistent with reports from the Cordova Channel [11]. The profiles show asymmetries between the acceleration and deceleration of the flood and ebb tides. In particular, the thickness was greater during periods of deceleration than acceleration of the tidal flow which suggests that once generated, the large eddies persisted after the maximum flow. Interestingly, at maximum ebb flow the boundary layer thickness appears to have reduced considerably to around 25 m. The observation implies that the boundary layer thickness was, however, relatively dynamic over the tidal cycle.

The profiles have also been plotted with a logarithmic ordinate in figure 1(b), which demonstrate that the mean velocity variation took an approximately linear form for elevations up to around 10 m above the seabed. Attempts were made to calculate the friction velocity from fitting the law of the wall to the velocity profiles. The estimates of the bed-stress which were derived from the friction velocity were found to exceed the stress computed using the variance techniques and the direct ADV measurements by approximately 25 %. Similar findings have been reported in the literature. In an attempt to shed light into these differences, it is useful to note that [14] consider the log-law to be applicable for elevations of around $z/h < 0.15$ to 0.2 in a two-dimensional open-channel. Therefore, the flow at this elevation may have been influenced by the outer-layer dynamics. However, it is plausible that the higher friction velocities computed using the log-law were due to the mean velocity not having been measured sufficiently close to the seabed. Furthermore, it could also be expected that there was an additional contribution from form drag which affected the mean velocity profiles.

Profiles of the Reynolds stresses corresponding to the equivalent periods of the tidal cycle as the mean velocity profiles are shown in figure 1(c). The largest stresses were observed near the bed and at around peak tidal flow. The stresses tended to very small values near the top of the water column for the peak flood. The stresses were approximately zero at around $z = 40$ m during the peak ebb flow, with the exception of one profile, where they tended towards zero at $z = 25$ m. Together, these results are consistent with the thickness of the boundary layer observed during the tidal cycle. During the ebb, the variation in the stress through the water column was approximately linear, as expected for a two-dimensional open-channel flow [14]. The variation in the flood profiles was less linear, with regions around 10 m in height observed where the stresses were relatively large or small compared to a linear decay.

Turbulence Intensities and Stresses Above the Bed

The time histories of the 5-minute mean velocity and the along-channel Reynolds stresses at an elevation of 5 m above the seabed during the flood-ebb tidal cycle are shown in figures 2(a) and (b). Both the ADV and ADCP results are shown for comparison. The close agreement between the two independent measurements of the mean velocity and the tress provides confidence in the reported values. Furthermore, it demonstrates that the majority of the along-channel stress could be sufficiently resolved in the experiment.

The Reynolds stress varied approximately in-phase with the mean flow. At peak flow the magnitude of the stress tended to a median value of around $0.014\,\mathrm{m^2\,s^{-2}}$. However, the histories were characterised by relatively short-term (i.e. less than 15 minute) variations in the stress over the tidal cycle. This was likely to be associated with the unsteady nature of the mean tidal velocity and the boundary layer.

Time histories of the standard deviations of the fluctuating velocities and the total turbulent kinetic energy, $q^2 = 0.5\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)$, observed during the same tidal cycle as previous are shown in figure 2(c). The magnitudes of these statistics also varied approximately in phase with the mean tidal flow and exhibited short term fluctuations.

The anisotropic ratios are shown in figure 2(d) and serve to elucidate the turbulence structure. These ratios tended to near constant values of $\sigma_v/\sigma_u = 0.75$ and $\sigma_w/\sigma_u = 0.55$ during non-slack periods of the tidal flow. We have also plotted the ratio $-\sigma_{uw}/q^2$ and the correlation coefficient $-\sigma_{uw}/\sigma_u\sigma_w$. These latter ratios also tended to approximately constant values, implying that the Reynolds stress and the intensities were closely related. The former result provides further support for the use of the ratio $-\sigma_{uw}/q^2$ as a simple turbulence closure model, as proposed by [3].

The results are compared with values reported in the literature in table 1. In general, the observed values agree favourably with the two-dimensional steady flow laboratory results reported by [14] of $-\sigma_{uw}/q^2 = 0.10$ and $-\sigma_{uw}/\sigma_u\sigma_w = 0.40$ at an elevation of $z/h = 0.1$. Comparisons with the atmospheric observations of [4] suggest that the vertical eddies in particular are physically more constrained in a tidal channel than in the atmospheric boundary layer, likely due to the confinement imposed on the eddies by the free-surface. The observations also align well with the ratio of $-\sigma_{uw}/q^2 = 0.14$ which was reported by [6] at an elevation of $z/h = 0.06$ during peak flow at the Puget Sound. The ratio $-\sigma_{uw}/q^2$ observed at Islay is slightly smaller than the value of 0.15 assumed by [3]. However, based on profiles of $-\sigma_{uw}/q^2$ presented by [14] it is hypothesised that the value assumed by [3] is more applicable at greater elevations from the bed and within the intermediate flow region.

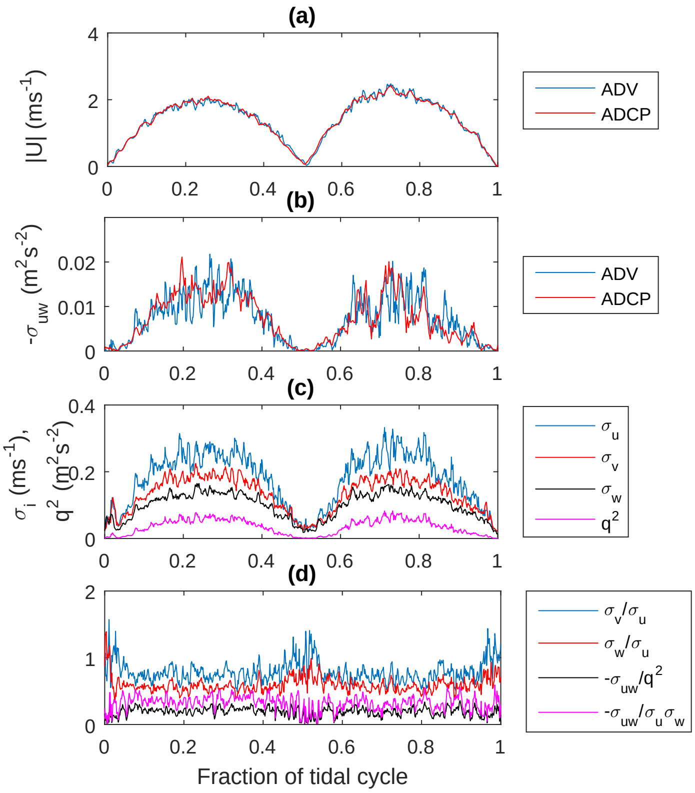

Figure 2: Time histories of the 5-min time-averaged streamwise velocity, along-channel Reynolds stress, standard deviation of the velocity fluctuations and the total turbulent kinetic energy at an elevation of $z = 5$ m.

	σ_v/σ_u	σ_w/σ_u	$-\sigma_{uw}/q^2$
Islay	0.75	0.55	0.12
Puget Sound [6]			0.14
Laboratory [14]	0.71	0.55	0.14
Atmosphere [4]	0.80	0.68	0.11

Table 1: Comparison of the turbulence statistics reported for tidal channels, open-channel flows in the laboratory and the atmosphere

Spectra Above the Bed

Velocity spectra and cospectra were computed to provide insights into the distribution of the turbulent scales at an elevation of 5 m at Islay. These results were obtained from 30 samples around peak flow which were linearly detrended and normalised by the variance. The averaged spectra for the flood flow are presented in figure 3 as a function of the non-dimensional wavenumber $kz = 2\pi f z/U$ (where f is the frequency in Hz) in order to facilitate testing of the similarity scaling law and have been smoothed at high wavenumbers for clarity. The spectra for the peak ebb tide were found to be quantitatively similar but are not shown for brevity.

The streamwise energy encompassed a relatively broad range of spectral scales, with a peak centered around $kz \approx 0.4$. This corresponds to a length-scale similar to the depth of the channel. In contrast, the spectral energy band of the lateral and vertical motion was comparatively more restricted with peaks corresponding to higher wavenumbers of approximately $kz = 2$ and $kz = 4$, respectively. The latter result is consistent with the dom-

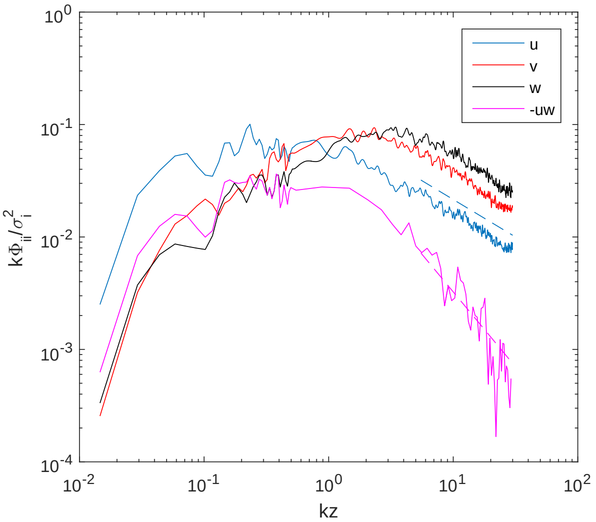

Figure 3: Normalised velocity spectra and the cospectra of the momentum flux observed at an elevation of $z = 5$ m above the bed during the peak flood tide. The predicted $k^{-5/3}$ and $k^{-7/3}$ spectral forms at high wavenumbers for the velocity spectra and cospectra are indicated by the dashed lines.

inant vertical motion being constrained by the seabed and having a length-scale approximately equal to z, as assumed by [17]. The peak of the cospectra corresponded to a non-dimensional wavenumber of $kz = 1$. A significant portion of the flux was therefore constrained to smaller scales due to the presence of the seabed. Given that the spectral peak corresponded to wavelengths greater than the bed, in line with [7], it is postulated that there was a contribution to the stress from flattened out eddies.

As is depicted in the figure, the streamwise velocity spectra appear to tend towards the $kz^{-5/3}$ proportionality predicted by Kolmogorov in the inertial subrange at the wavenumbers of $kz > 2$. The inception of an integral subrange in the vertical motion appears to correspond to higher wavenumbers of around $kz > 8$. Furthermore, at wavenumbers exceeding $kz > 0.5$ the co-spectra also decay at a rate that aligns well with the $kz^{-7/3}$ proportionality predicted by [18].

Conclusions

The observations presented within this study have provided an opportunity to draw further insights into the characteristics of boundary-layer driven turbulence in a rapid tidal flow. The distributions of the Reynolds shear stress through the water column and the structure of the turbulence above the seabed at the spring tide were found to be qualitatively consistent with the form expected for a two-dimensional open-channel flow and other tidal channels reported in the literature. The close relationship between the instantaneous Reynolds stress and turbulent kinetic energy in particular also suggests that simple closure models could be useful for describing the turbulent structure near the bed for tidal channels similar to Islay.

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