Turbulence and Bottom Stress in Grand Passage and Minas Passage

Final Report

Submitted by

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to

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A. Motivation

The need for improved knowledge of turbulence in high-flow tidal channels has arisen because of developments associated with extracting renewable electrical energy from these natural flows using in-stream hydrokinetic energy conversion devices (i.e. turbines). The wide range of scales in turbulent motions are such that, instantaneously, the flow past the turbine varies significantly across the area swept out by the blades, in principal even reversing direction. These variations affect not only turbine performance in terms of energy production, they produce time-varying loads on the blades which lead to material fatigue and thus shorten the turbine operating life (Marsh, 2009).

To be economic, turbines will have to be deployed in arrays. Consequently, a central question concerns optimal array design, given the interaction among turbines via their wakes (Myers and Bahaj, 2010). In a recent study, Churchfield et al. (2013) used a sophisticated numerical modelling technique -- Large Eddy Simulation (LES) -- to investigate the interactions between the turbulence generated in turbine wakes and turbulence in the ambient flow. They predict that turbines in a closely-spaced array can – depending upon the array geometry – perform more efficiently than an isolated turbine. However, as stated in their conclusions, the accuracy of these predictions will be assessed "as experimental *field data* become available" (my italics).

Finally, turbulence intensity is not a simple function of the local flow conditions. One cannot -- based on the flow speed and water depth alone -- predict the levels of turbulence with any degree of accuracy. The reason for this is that turbulence in tidal channels is generated by the interaction of the flow with the seabed, and the bottom topography is highly variable from location to location. Furthermore, the local seabed conditions at the turbine site are not sufficient. As the results presented in this report demonstrate, the bathymetry upstream of the turbine can be critically important, leading to pronounced ebb/flood asymmetry in turbulence intensity.

To summarize:

- Knowledge of turbulence is necessary to optimize turbine design both for turbine performance and turbine durability.
- Numerical modelling of turbulent flows relevant to tidal power has reached an advanced stage of development
- Turbulent conditions are highly site specific
- Field data to validate these models are lacking

These four points together point to the need for an approach in which turbulence measurements are combined with turbulence models to characterize the flow variability at sites targeted for tidal power development, and motivated the present project. At the same time – as might be inferred from the lack of suitable field data identified by Churchfield et al. -- making turbulence measurements in high-speed flows presents a significant technical challenge. While significant progress has certainly been made on this front (e.g. Lu et al., 2000; Milne et al., 2013; Thomson et al., 2012), approaches to this challenge have by no means been exhausted. Thus, another motivation for the project was to test several different turbulence measurement techniques.

B. Project Overview

The original goal of this project was to obtain estimates of 2nd-order turbulence quantities – e.g. turbulent kinetic energy (TKE) and Reynolds stress – using an instrumented bottom lander that we had developed for bottom boundary layer studies on the continental shelf, and to do so in both Grand Passage and Minas Passage. In Grand Passage this goal was fully realized in an experiment carried out in 2012 (see Section B below, and Appendix A). For Minas Passage, the plan had been to take advantage of a research mission to the Bay of Fundy on the *CCGS Hudson* led by colleagues at the Atlantic Geoscience Centre of the Bedford Institute of Oceanography. However, the number of days available for the mission precluded operating in the Passage, and so this plan had to be abandoned.

Meanwhile, we had been carrying out a tidal resource assessment study of the tidal channels in the Digby Neck and Southwest Nova Scotia region using moored ADCPs (see McMillan et al., 2013). For some of these moorings – those in water depths greater than 30 m – the ADCP was mounted in a streamlined underwater buoyancy system (SUBS) tethered to an anchor on the seafloor. The pitch and roll standard deviations from these deployments during full flood and ebb were quite high (often greater than 10 degrees), indicating that the SUBS was quite unstable. This observation led us to investigate other streamlined buoyancy systems, and to a proposal submitted in June 2012 to OERA for a budget modification to allow purchase of a “Stablemoor” buoy, built by (then) Flotation Technologies in the U.S. and represented in Canada by Romor Ocean Solutions. This proposal was approved in late August 2012.

There then began an extended interaction with FloTec on modifications to the Stablemoor design, which were finally resolved when we (Richard Cheel and myself) drove to visit the company in Maine in November 2012. These modifications were to permit installation of both upward- and downward-looking ADCPs. Later, as result of a meeting with Nortek-AS in Oslo in early February 2013, we were offered the loan free-of-charge of new instruments for deployment on the Stablemoor platform. Nortek had developed for beta-testing two broadband Doppler devices operating at 1 MHz: a 4-beam AD2CP with bottom-track, and a single-beam ADCP. Nortek’s interests were in having the performance of these instruments tested in high-speed tidal currents. Subsequently, in late February discussions took place with Rockland Scientific International (RSI, Victoria, BC) regarding the possibility of mounting their shear probe turbulence sensor – the Microrider – on the Stablemoor. This required further modifications to the design. A proposal for an ENGAGE grant to enable the collaboration with RSI was submitted to NSERC in April 2013, and awarded in early May 2013. The Stablemoor design was finalized for the 2nd time in March 2013, and the buoy was delivered in early July, 2 weeks before the scheduled start of the field experiment (see Section B below, and Appendix B).

With the Stablemoor, and the collaborations with Nortek and RSI, the second goal of the project became – rather than turbulence and bottom stress in Minas Passage -- to obtain a novel set of time series measurements of turbulence in mid-water column, and thereby test a technology suitable for turbulence measurements at nominal hub height that could in principle be deployed in high flow conditions anywhere, including Minas Passage.

C. The Grand Passage Turbulence Experiments

The 2012 Experiment

Of the many results from the 2012 experiment, there are three to highlight. The first is embodied in Figure 1, in which the root-mean-square (RMS) fluctuations of each of the four along-beam ADCP velocities plotted against the friction velocity, u_*, obtained from the vertical profile of the flow speed via the law-of-the-wall. It is most important to note that these two quantities are entirely independent: one, the RMS fluctuation is turbulence-based, while the other, u_*, is based on the time-averaged speed, i.e. with turbulence removed.

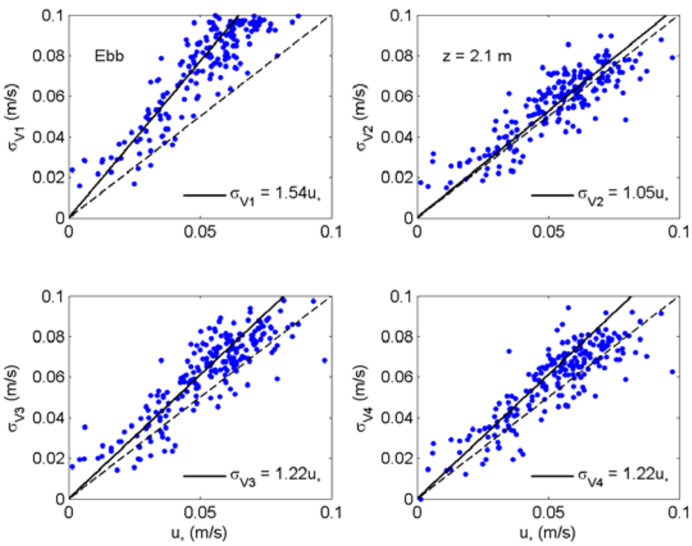

***Figure 1**. RMS beam velocities vs u_*. The solid lines indicate the expected relationship based on laboratory and atmospheric boundary layer measurements. The dashed line is the 1:1 line.*

While the individual estimates in Fig. 1 are scattered, this degree of scatter is typical of turbulence measurements. The results in Fig. 1 are clearly consistent with the accepted relationships between the (anisotropic) RMS velocity fluctuation amplitudes in the constant stress layer of a rough turbulent wall layer and the friction velocity.

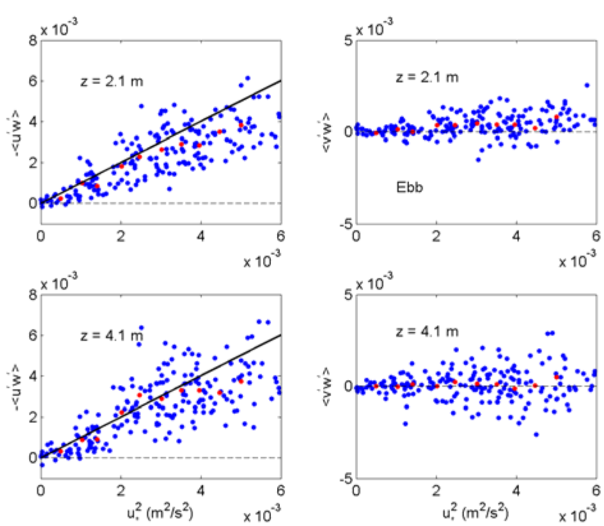

***Figure 2**.Reynolds stresses vs friction velocity squared at two different heights above bottom. The panels at left show the along-channel Reynolds stress, with the solid line indicating 1:1. The panels at right are the cross-channel Reynolds stress estimates, the dashed line indicating zero.*

Another comparison between independent estimates is shown in Figure 2: that is, independent estimates of the vertical momentum flux. In this case the turbulence-based estimate is the Reynolds stress, $-\langle u'w' \rangle$, while the mean flow estimate is u_*^2. The Figure clearly indicates that, within the constant stress layer, the ADCP estimates of the turbulent stresses are correct, being both comparable to the law-of-the-wall mean flow estimates in the along-channel direction, and consistent with the expectation of near-zero cross channel (or as in this case cross-isobath) stress in quasi-steady unstratified flow through channels much narrower than the Rossby radius.

The third result from the 2012 experiment worth highlighting here is shown in Figure 3, in which q, where $q^2/2$ is the TKE per unit mass, is plotted against the depth-averaged speed, U. These results indicated that the RMS turbulence intensity – a variable of interest to turbine design engineers – can be as much as 20% of the mean flow speed. The values in Figure 3 are not unlike those that have been measured in the wind turbine industry, and indeed not unlike values that have been previously reported for flow in tidal channels. However, the point here is that, given the results in Figures 1 and 2 above, there is a solid basis for believing that the values in Figure 3 are accurate.

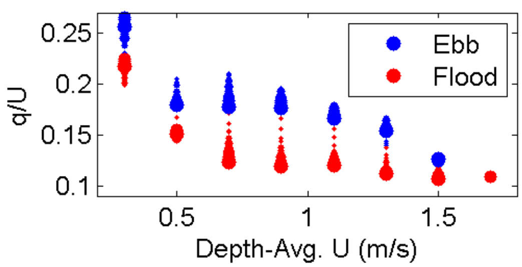

***Figure 3**. RMS turbulence intensity q, normalized by the depth-averaged mean speed U, vs. U, for heights between 2.1 and 10.1 m. Symbol size increases with height.*

Further details about the 2012 experiment, as well as other results, can be found in Appendix A.

The 2013 Experiment

This experiment was of two weeks duration, 29 July to 9 August. A bottom pod with a 600kHz RDI ADCP and a 1 MHz Nortek 5-beam AD2CP (now called a Signature 1000) was deployed at the location indicated in Figure 4. As indicated in Figure 4, the Stablemoor was deployed nearby, in the first week with the Nortek single-beam Doppler in the nose, in the second with the RSI Microrider in the nose. The Stablemoor, with its instrument complement in the second week, is also shown in Figure 4. As indicated in Section A of this report, the Stablemoor was delivered just 2 weeks before the experiment, which gave us no time for testing prior to going into the field. As it turned out, due to a miscommunication with the company, the pivot point was located in the wrong location and so the buoy was too far from level during the first deployment. By adding buoyancy to the tail – i.e. the three yellow floats in Figure 4 -- and lead ballast in the nose, we were able rectify the problem in time to proceed with the Microrider phase of the experiment in the second week. Also during the second week we carried out a series of vertical profiles with RSI's profiling instrument (the Vertical Microstructure Profiler, VMP), thereby obtaining quasi-synoptic measurements of the cross- and along-channel distribution of turbulence microstructure in the vicinity of the Stablemoor while it was in place. These data are summarized in Appendix B.

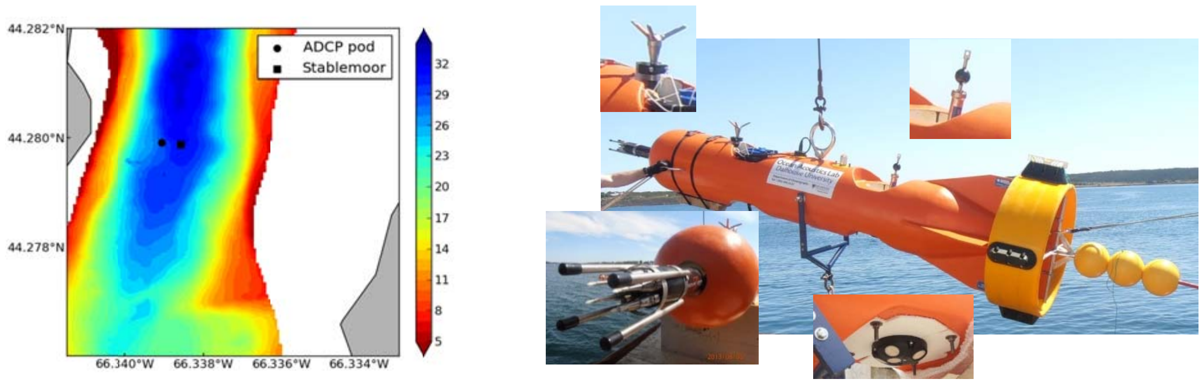

__Figure 4.__ Left: Bathymetry in Grand Passage and the locations of the ADCP bottom pod and Stablemoor buoy. Right: The Stablemoor buoy and associated instruments during the 2nd week of the 2013 experiment: clockwise from lower left, the RSI Microrider in the nose, with 4 shear probes and the probe guard; a Nortek Vector single-point acoustic Doppler velocimeter; a JFE single-point electromagnetic flowmeter; and a downward-looking Nortek bottom-tracking AD2CP.

The central result from the experiment so far -- the rate of dissipation of TKE from Microrider on the Stablemoor --is presented in Figure 5. While preliminary, the estimates exhibit the expected dependence on average of dissipation on the cube of the mean flow speed (for speeds high enough that the turbulence estimates are well above the noise).

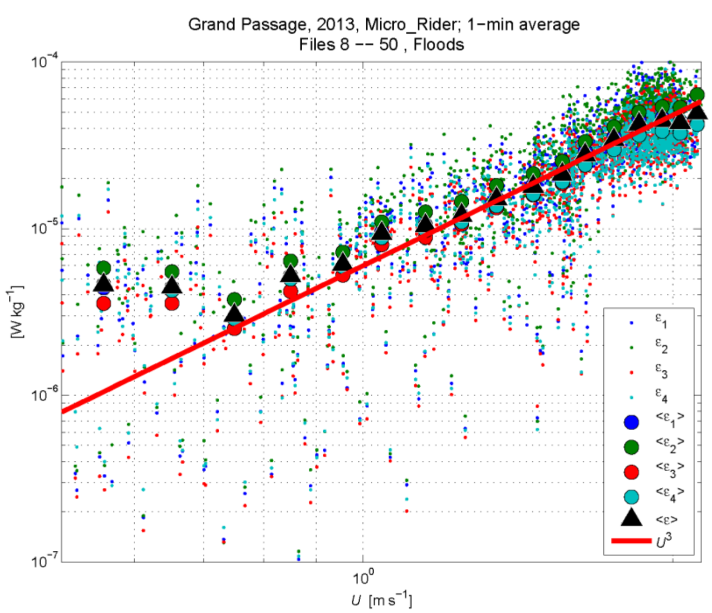

__Figure 5__. Estimates of ε, the rate of dissipation of TKE, vs. mean flow speed U, from the four shear probes in the Microrider on the Stablemoor. The small dots denote individual estimates, the larger solid circles the averages within equal speed intervals, and the black triangle the latter averaged over the 4 probes. The red line indicates a linear dependence of ε on U^3: i.e. consistent with turbulence dissipation and production being proportional to each other.

While not shown here, it is also very encouraging that the estimates of dissipation from the bottom-mounted ADCP nearby at the same 10 m height above bottom are very comparable: i.e. 5

x 10^{-5} W/kg at 2 m/s flow speed. Thus, we have successfully demonstrated that time series of turbulent velocities can be directly measured from a moored buoyant streamlined package at mid-depth in high-speed flows, and therefore that the revised 2nd goal of the project has been met.

The results from the 2013 experiemnt are the basis for a central component of doctoral student Justine McMillan's dissertation. Also, as indicated in Section E below, we have presented the preliminary results at several international meetings, including the Ocean Sciences Meeting and the European Geophysical Union General Assembly, and are currently writing up the technical aspects for publication.

D. Training

Doctoral student Justine McMillan, Research Associate Richard Cheel and former Research Associate Doug Schillinger (now the East Coast representative with RBR Ltd.) have all been actively involved in this project.

E. Synergy

One of the successes of this project has been the impetus/opportunity it provided for add-on projects which could not have happened otherwise. Specifically, the purchase of the Stablemoor resulted in the collaborations first with Nortek and then with RSI, which in enabled the NSERC Engage Grant with RSI and thereby the Microrider and VMP data sets. Without the OERA seed funding, none of this would have happened, and we would not have developed this technique for turbulence time series measurement at mid-depth. The results from the experiment are also providing essential input to the eddy-resolving turbulence modelling being carried out by colleagues Drs. Andrew Gerber and Tiger Jeans (Univerisity of New Brunswick) as part of the ecoEII project led by Dr. Richard Karsten (Acadia University). This project is also mentioned below in Future Directions.

F. Dissemination

Conference Proceedings

Hay, A. E., J. McMillan, R. Cheel and D. Schillinger, Turbulence and drag in a high Reynolds number tidal passage targetted for in-stream tidal power, *Proc. Oceans'13*, San Diego, USA.

Presentations

McMillan, J., A. E. Hay, and R. G. Lueck, Vertical profiles of turbulence metrics in Grand Passage, Nova Scotia, to be presented at the ICOE, Halifax, November 2014.

Hay, A., R. Lueck, F. Wolk and J. McMillan, Turbulence measurements from a streamlined instrument platform moored at mid-depth in a swift tidal channel. Presented at the Ocean Sciences Meeting, Honolulu, Hawaii, 23-28 Feb 2014.

Wolk, F., R. Cheel, P. Stern, A. Hay, and R. G. Lueck, A moored instrument for turbulence measurements in swift tidal channels, Presented at the Ocean Sciences Meeting, Honolulu, Hawaii, 23-28 Feb 2014.

Hay, A., R. Lueck, F. Wolk and J. McMillan, Turbulence measurements from a moored platform at mid-depth in a swift tidal channel. Presented at the European Geophysical Union General Assembly, Vienna, Austria, 27 Apr-2 May 2014.

Hay, A. E., J. McMillan, R. Cheel and D. Schillinger, Turbulence and drag in a high Reynolds number tidal passage targetted for in-stream tidal power, presented at Oceans'13, San Diego, USA, 23-26 Sept. 2013.

G. Achievements Relative to the Original Objectives

The proposal stated "The proposed project will be the first comprehensive study of flow and turbulence in these tidal passages." This has been achieved, though only in Grand Passage, for the reasons given in Section B.

The proposal also stated that the results would span "the full spectrum of relevant time scales from days to 10s of Hz, and spatial scales from 2 centimeters to the full water depth". This too was achieved.

The proposal stated that the results would provide:
" (a) a basis for the assessing turbulence-induced stresses on cables and turbine blades;
(b) a basis for assessing seabed mobility and stability; and
(c) a basis for testing the next generation numerical models turbulence simulation capability."

With regard to (a), the results include estimates of the bottom drag coefficient, turbulent shear stress and the mean rms turbulent velocities in the bottom boundary layer from the ADCP and MAVS, all of which can be used to estimate the stresses on cables lying on the seafloor. Similarly, the estimates of these same quantities in mid-water column from the ADCP and the Stablemoor-borne shear probes provide means to estimate stresses on turbine blades.

For (b) the bottom boundary layer measurements listed above also apply. In addition, in parallel this project, one of my postdocs – now Assistant Professor at Virginia Tech -- Dr. Nina Stark and I carried out extensive measurements of seabed properties using her free-fall cone penetrometer, grab samples, bottom photography and multi-beam sonar surveys.

For item (c), we now have an extensive data set on turbulence in Grand Passage, which can be used and is being used – see section H below – to validate the turbulence-resolving numerical model being developed for Grand Passage by our UNB colleagues, Drs. Gerber and Jeans. Their model is a Detached Eddy Simulation (DES), and has been developed to run in highly-parallelized mode on Graphics Processing Units (GPUs).

H. Conclusions, and Future Directions

We have demonstrated that estimates of second-order turbulence quantities obtained using acoustic remote sensing techniques – i.e. from broadband ADCP data via the variance method -- in a moderate-flow tidal channel (Grand Passage) are:

- self-consistent: e.g. the estimates of u_* from the turbulent shear stress agree with estimates from the mean velocity profile;
- consistent with atmospheric boundary layer measurements (e.g. the ratio of rms turbulent velocity components to friction velocity in the constant stress layer);
- consistent with independent direct measurements turbulence: i.e. the estimates of turbulence dissipation rate using the shear probes mounted on a streamlined platform at mid-depth;
- consistent dynamically: i.e. in a location where bottom contours were straight and parallel to the mean flow direction, the cross-stream Reynolds stress was zero.

This high degree of consistency indicates that the estimates of rms turbulence levels at mid-depth column outside the constant stress layer – i.e. 10 to 20% of the mean flow speed (Figure 3 here, Figure 24 in Appendix A) – are reliable, and can be used by turbine design engineers and tidal power developers to estimate performance and operating life at this site.

While the variance method has an established history, having been employed with broadband ADCP data for the first time to my knowledge by Stacey et al. 1999 (but in a low flow channel), it is important to recognize that only time-averaged estimates of turbulence quantities are obtained. Furthermore, despite the promising results reported here, there are questions that remain, in particular the Doppler noise level at higher flow speeds than the 2 to 3 m/s speeds in Grand Passage (see, for example, Richard et al., 2013).

Further analysis of the data collected in this project, particularly the shear probe data from the Stablemoor deployment, is ongoing and being carried out by doctoral student Justine McMillan for her thesis. As indicated above, those results as well as the other measurements from the present project are being used to validate the turbulence model being developed at UNB as part of our ecoEII project. Also as part of ecoEII, next we'll be carrying out further measurements with the Stablemoor in higher speed flow conditions, in Petit Passage initially and – pending available funding – in Minas Passage.

The development of the FAST platform by FORCE, and the collaboration with FORCE and Nortek on the Vectron Project, will result in a new and unique capability for turbulence characterization in Minas Passage. The Vectron – a wide-baseline bistatic acoustic Doppler device purpose-built for 3-component turbulence measurement in high-speed flows – will provide measurements at heights of 8 to 10 m above the seabed. While this is a major step forward, it does not meet the needs of all berth holders, those whose planned hub heights are substantially farther above bottom at ca. 20 m height or more. Measurements at these heights requires something else, a measurement need which can be met by the Stablemoor platform, suitably instrumented.

J. References

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