Turbulence Measurements Using Non-Acoustic Sensors in a High-Flow Tidal Channel

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This paper introduces an instrument solution for in-situ turbulence measurements based on a combination of sensor technologies that have been tested in offshore deployments. At the core of the sensor suite is the velocity shear probe, which is a standard sensor for measuring dissipation scale turbulence in the ocean. The shear probe resolves turbulent length scales near the dissipation range. We evaluate the application of the shear probe in tidal channel flows, presenting data examples of measurements from a vertical profiler deployed in a tethered free-fall mode. The data resolves turbulent velocity fluctuations over length scales of several centimeters to an order of 1 m. The shear probe sensor has a wide dynamic range, resolving vertical changes of turbulent kinetic energy dissipation ranging from 10^{-10} *to* 10^{-4} *W/kg. The results demonstrate the suitability of the shear probe-based measurement to understanding the nature of tidal flows over length scales associated with turbine blade dimensions, rotor dimensions, array separations, and array footprints.*

NOMENCLATURE

W = apparent vertical velocity due to profiling
u = horizontal velocity fluctuation due to turbulence
U = total velocity
α = angle of attack
ν = kinematic viscosity of water
dBar = unit of pressure almost identical to a depth change of 1m
VMP = Vertical Microstructure Profiler
TKE = turbulence kinetic energy

1. Introduction

In characterizing tidal energy resources, turbulence measurements have been identified as a requirement for assessing the energy available in the stream for extraction by tidal turbines, as well as optimizing designs of the turbine devices themselves. The highly energetic flows found in tidal channels typically are not laminar and turbulence acts as a retardant on the flow. It is therefore important to characterize and quantify the rates and locations of energy dissipation. The vertical structure of the turbulent energy dissipation is highly variable and not necessarily correlated with the vertical structure of the flow field [1], affecting predicted energy yields of the turbines.

From a turbine device point of view, numerous studies (e.g., [2]) have explored the effects of turbulence on the loading of the turbine blades. A recent case study conducted by TÜV SÜD NEL Ltd. [3] showed that there is a general consensus in the tidal energy sector that turbulence intensity significantly impacts the loading on turbines and their performance. Therefore, in-situ turbulence measurements with a spatial resolution of 0.01–1 m (i.e., the turbine blade scales) are necessary to assess and monitor the turbulence field at tidal turbine sites. Key turbulence parameters that need to be quantified are the dissipation rate of turbulence kinetic energy and the velocity fluctuations of the turbulence and their wavenumber spectra.

This paper discusses techniques and tools that are commonly used in the oceanographic research community to measure ocean turbulence in the context of climate variability and ocean circulation. Since application of these tools in the tidal energy context will be of increasing importance in the coming years, we describe here the instrumentation, sensors and procedures for obtaining turbulence profile measurements in tidal channels.

2. Instrument Description

A vertical profiler is a commonly used instrument for the measurement of oceanic turbulence microstructure [4]. Microstructure in this context is defined as the spatial scales where turbulent velocity fluctuations are damped out by the fluid's molecular viscosity, typically on the order of millimeters to centimeters. These scales are also called the dissipation range. Several models with varying depth ranges and sensor configurations are available, optimized for specific operating environments, such as coastal, offshore and deep sea. In this study we used the VMP-500 (Fig. 1), which carried microstructure velocity probes (as called shear probes), high-resolution temperature sensors (thermistors) and a number of ancillary sensors, such as high-accuracy CTD sensors, accelerometers, and tilt sensors. The VMP-500 is designed for coastal

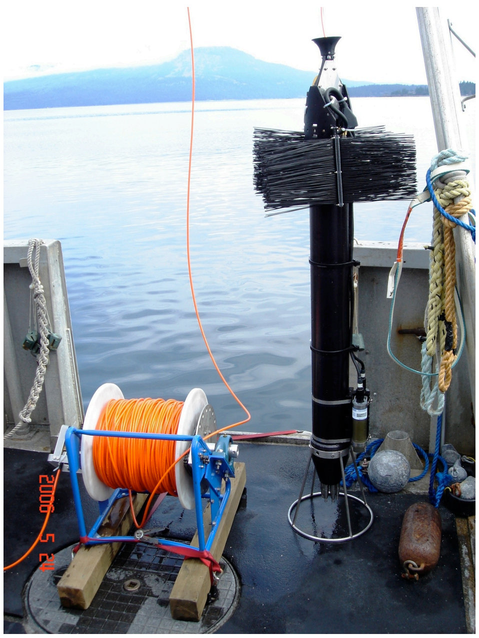

Fig. 1: The VMP-500 Profiler and a small hand-winch to manage its electro-mechanical tether.

and shelf-region operation. Data are transmitted through a four-conductor cable and recorded with a shipside data acquisition computer. Power to the profiler is supplied through the deployment cable, which allows for virtually unlimited deployment time.

3. Turbulence Profiling Procedures

The VMP is deployed from a drifting ship in a "tethered free-fall mode", where the profiler is connected to the ship by a cable or line that is paid out at a rate slightly faster than the sum of the profiler's fall speed and its rate of horizontal advection away from the ship. Due to the slack tether, the fall speed is constant and independent of ship motions. Brushes at the top end of the profiler provide drag, slowing the profiler to a constant fall speed of approximately 0.7 m s^{-1}. This speed is a trade-off between the operational desire to conclude a profile as quickly as possible and the requirement to profile slowly to avoid generating vibrations or instabilities in the motion of the profiler. During the profile, the ship typically drifts with the current and the wind. The profiler is launched from the upwind side so that the ship drifts away from the tether cable to avoid snagging it beneath the ship. The operator deploying the profiler feeds the line into the water at a rate that will result in a certain amount of slack cable being visible at the water surface. Instead of drifting, the ship can also steam ahead slowly at a rate of 0.5–1 m s^{-1}. The main limitation is the length of the tether and its maximum rate of deployment.

4. Turbulence Sensors

Turbulence sensors are mounted on the nose of the VMP, pointing downward. In this position, the sensors are not affected by any turbulence created by the profiler itself. The primary sensor for the measurement of turbulence is the shear probe (Fig. 2), which consists of a piezo-ceramic element, 12 mm long and 1.5 mm wide,

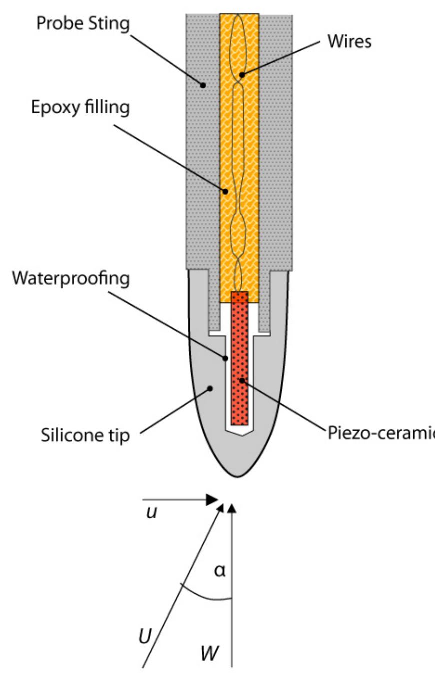

Fig. 2: Shear probe schematic. W is the apparent vertical velocity due to profiling, u is the horizontal velocity fluctuation due to turbulence, U is the total velocity, and α is the angle of attack.

that is embedded halfway into a hollow stainless steel support sting.

The free end of the piezo beam is encased in a flexible silicone rubber tip that has the shape of an axially symmetric airfoil.

As the probe moves axially through the water at the speed W (the fall-rate of the profiler), the horizontal component of the turbulence velocity, u, induces a lift force over the airfoil. The piezo-ceramic element translates this lift force into an electric charge, which is differentiated by the VMP's signal conditioning electronics to yield a voltage, $E = sW\partial u/\partial t$. With Taylor's hypothesis, the time derivative of u is converted into a spatial derivative, to yield the vertical shear of horizontal velocity, $\partial u/\partial z = W^{-2}s^{-1}E$, where s is the sensitivity of the probe, which is established during calibration. Details of the calibration procedure are given in [5]. The shear probe is sensitive to only a single component of velocity oriented at right angles to its axis. Therefore, two shear probes in parallel, with one rotated by 90° around its axis, can provide both components of vertical shear, $\partial u/\partial z$ and $\partial v/\partial z$. When the shear probe is used in a horizontal configuration (such as towing or on a glider), the probe measures the horizontal shear of two velocity components, namely $\partial w/\partial x$ and $\partial v/\partial x$, where x is the quasi-horizontal direction of profiling.

The smallest spatial scale resolved by the shear probe is determined, to first order, by the length of the probe tip, which is approximately 1 cm. The largest resolved spatial scale is determined by the stability of the profiler as it moves through the water column. The profiler body is inert to turbulent eddies with scales much smaller than the profiler length. However, large eddies with sizes comparable to (and larger than) the length of the profiler will move the profiler and attenuate the velocity detected by the shear probes. That is, a freely falling vertical profiler acts as a high-pass filter to velocity fluctuations with scales larger than the length of the profiler. The VMP-500 is approximately 1.5m long and the largest spatial scale that can be resolved is 1 m.

The other outstanding characteristic of the shear probe is that it is extremely sensitive and can detect velocity fluctuations smaller than 1 mm s^{-1}. In practice, the signal resolution is limited by profiler vibrations and this holds true for all relative velocity sensors.

5. Data examples from a tidal channel

Profiles of turbulent vertical shear were collected with a VMP-500 in Sansum Narrows (Fig. 3), which is a swift tidal channel near Victoria, British Columbia, Canada, separating Vancouver and Saltspring Islands. The profiles were collected downstream of a sill when the flooding tide was running northward through the channel with typical speeds of 2 m s^{-1}. The ship was drifting with the current while the VMP descended at a rate of 0.65 m s^{-1}. Data for this profile were collected on 24-May-2006 at 13:26 local time (file VMP_012_005). The VMP was equipped with two standard velocity shear probes (SPM-1000), one high-resolution temperature probe (FP07-1000), and one high-resolution conductivity sensor (SBE7-1000). All vertical axes in the figures presented here are expressed as pressure, in units of dBar. One unit of pressure is almost identical to a depth change of 1 m. Consequently oceanographers use pressure and depth interchangeably, unless the difference is important. The shape of the temperature profile (Fig. 4) shows a water column that is, for the most part, stably stratified with temperature decreasing from 10.3 °C at the surface to 9.4 °C at 100 m depth. A seasonal thermocline between the surface and 15 m depth overlays a weakly stratified mixing layer that extends down to 55 m.

Fig. 3: Chart of Sansum Narrows, located approximately at 48.80° N, 123.55°W

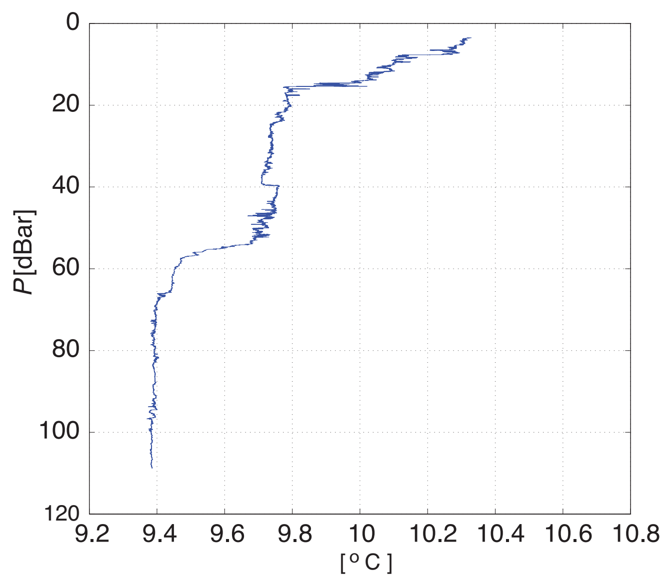

Fig. 4: Temperature profile from Sansum Narrows collected with the high-resolution thermistor on the VMP-500.

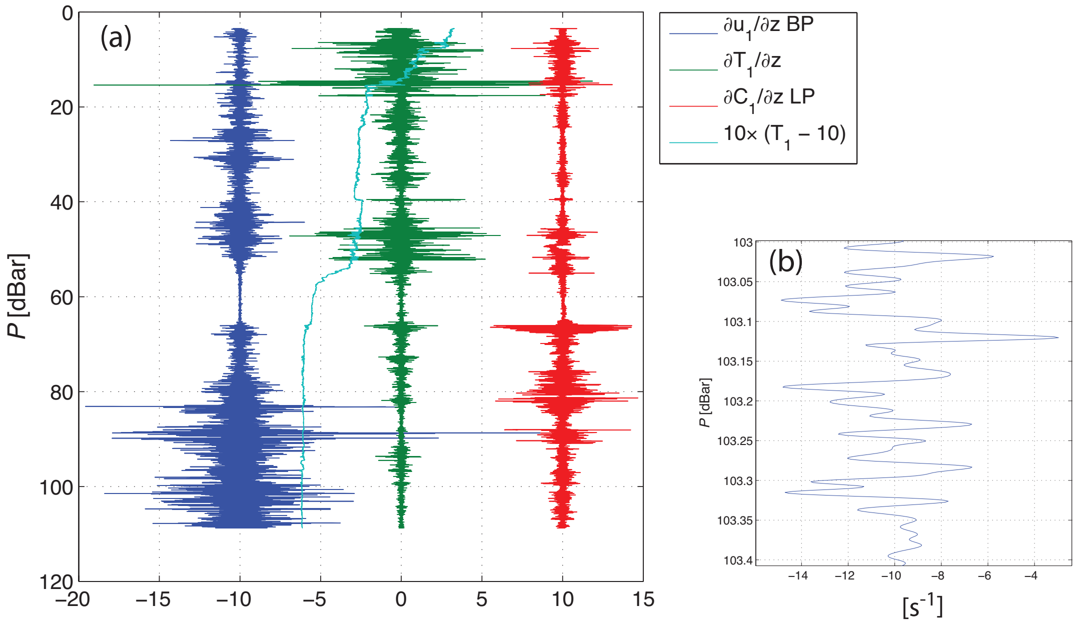

Fig. 5: **(a)** Profiles of shear (blue) and the vertical gradients of temperature (green) and conductivity (red). The data are band pass filtered between 0.4 and 50 Hz for display purposes only. A scaled version of the temperature profile (cyan) is shown for reference. The shear and the conductivity gradients have been shifted left and right by 10 units for clarity. **(b)** A 40 cm detail of the shear starting at 103m depth highlights the centimeter-scale variations resolved by the shear probe.

Between 55 m and 65 m there is another thermocline, and below 65 m the water column in nearly homogeneous (well mixed). The temperature profile was taken with the fast-response thermistor, so it also reveals numerous temperature inversions on sub-meter scales that are caused by turbulent overturns. For example, the abrupt increase of temperature at 40 m and the numerous fluctuations between 45 and 55 m give a clear, but indirect, indication of turbulence. During the deployment of the profiler, vigorous turbulent mixing was evident in the form of surface boils of smooth and nearly wave-free water (local updrafts) and convergences of very choppy waves (local downdrafts). Figure 5 shows the vertical profile of shear, the gradient of temperature and electrical conductivity (mostly due to salinity). Only one of the shear sensors is shown here for clarity. Clearly, the entire water column is turbulent, with the exception of a 10m thick quiescent layer between 55 and 65 m, corresponding to the depth of the deeper thermocline. The small-scale velocity shear (blue line) reaches levels of around 2.5 s^{-1} in the surface layer and around 10 s^{-1} in the lower turbulent layer. The high-resolution profiles of the vertical gradients of the two scalar turbulent components, $\partial T/\partial z$ (green line) and $\partial C/\partial z$ (red line), also reflect the vertical variations of the turbulence in Sansum Narrows. Panel (b) in Figure 5 presents a high-resolution detail of the shear profile over a 40 cm depth range starting at 103 m, that shows the sub-centimeter resolution of the shear probe.

A standard parameter that is used in oceanographic research to describe the strength of turbulence is the rate of dissipation of turbulent kinetic energy (TKE), which can be calculated from the variance of the measured velocity shear using

$$\epsilon = \frac{15}{2}\nu\overline{\left(\frac{\partial u}{\partial z}\right)^2}.$$

where ν is the kinematic viscosity of water and the over-bar denotes a vertical (or depth) average (typically taken to be 0.5–1 m). Figure 6 shows the profile of the rate of dissipation of TKE, computed from

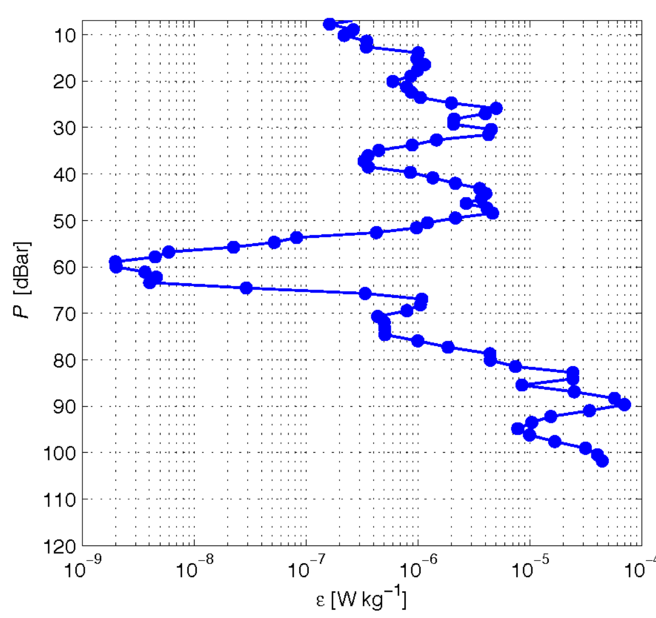

Fig. 6: The vertical profile of the rate of dissipation of TKE. The estimates are spaced approximately 1.25 m vertically.

the shear data following accepted processing procedures [6,7]. The vertical depth bins were approximately one meter. The rate of dissipation can vary by many factors of ten in a tidal channel. For Sansum Narrows the range is almost 10^5, during this profile.

Finally, the shear probe signal can be numerically integrated to give a direct expression of the small-scale velocity fluctuations, *u*. For the shear profile in Figure 5, the velocity profile is shown in Figure 7, with the inset graph showing a detail of the profile. The high spatial resolution of the shear probe signal is evident in the detail, with velocity fluctuations on scales of ~ 1 cm being resolved.

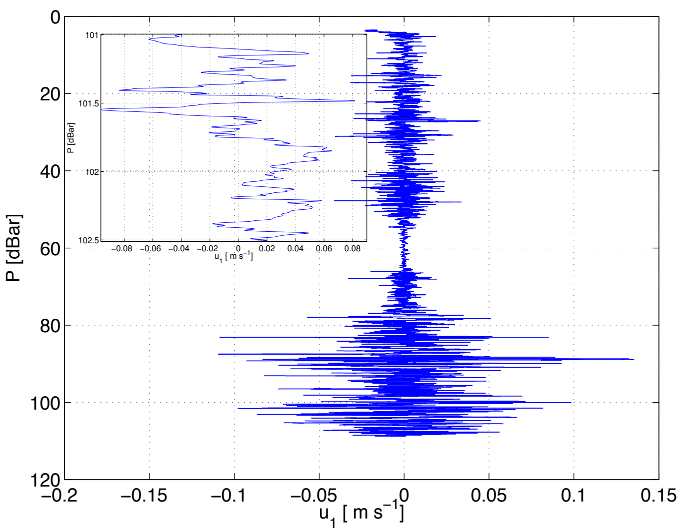

Fig. 7: Profile of turbulent horizontal velocity computed by numerically integrating the vertical shear profile from Fig 5. The inset shows a 1.5 m detail of velocity starting at 101 m depth, highlighting the centimeter-scale variations resolved by the shear probe.

6. Summary

- Turbulent velocity measurements with fine spatial resolution are a key requirement for the operation and design of tidal-energy turbines. Vertical microstructure profilers can satisfy this requirement.
- The VMP is a standard instrument for measuring turbulent velocity fluctuations and is used routinely by the academic research community for in-situ observations. The key sensor of the VMP is the shear probe, which resolves turbulent velocity on scales between 0.01–1 m and does so with extremely low noise.
- Data from a deployment of a VMP in a swift tidal channel demonstrate the application of the instrument in a tidal regime. Turbulent parameters of velocity, velocity shear and energy dissipation rate are well resolved. In addition, high-resolution gradients of temperature and conductivity can provide additional information about the turbulent structures in the water column.

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