Quantifying Turbulence in Tidal Channels

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SUMMARY

This paper discusses methods and instrumentation solutions for the reliable measurement of flow turbulence in tidal channels, which are the preferred locations for tidal energy generation. While the natural geographic constrictions of tidal channels accelerate the flow, thereby increasing the energy density available for extraction, topographical features and curvatures of the channels create intense turbulence in the flow. Numerical models and scale model tests in laboratories attempt to emulate turbulence and predict its impact on the energy converters. However, direct measurements *in situ* are required to assess and understand the full impact of the turbulence effects and to account for local effects of the sites.

Unfortunately, turbulence is extremely difficult to measure in the harsh conditions that are typical of tidal channels. The most advantageous measurement techniques involve a mix of non-acoustic and acoustic sensors. These can be mounted on the seabed or deployed on anchored floating platforms, which provide measurements in the middle of the water column, at the hub height of tidal turbines. Combining non-acoustic and acoustic sensing technologies makes it possible to characterize the entire turbulent velocity spectrum pertinent to tidal energy generation. The Nemo system is a floating platform that carries a combination of sensing technologies to measure turbulence. Nemo has been developed in Canada out of a collaboration between industry and academia. The system has been tested in tidal channels in Canada and the UK.

Two research and develop projects *InSTREAM* and *TiME* are described, which establish methodologies and instrumentation to fully characterize the turbulent flow in and around tidal energy sites.

1. INTRODUCTION

Tidal channels are the preferred sites for commercial energy extraction, because these natural geographic constrictions focus and accelerate the flow, which increases the energy density available for extraction by tidal turbines. These sites often have abrupt topographical features and curvatures that cause the tidal flow highly turbulent. In some channels flow speeds can exceed 5 m/s, resulting in extreme turbulence levels comparable to those found in a vigorous beach surf zone. The unsteady, turbulent flow speed represents a significant challenge for the design and operation of tidal energy turbines. Insufficient understanding and prediction of the turbulent flow, therefore, leads either over-engineering of the devices, which increases capital cost, or under-engineering, which leads to shorter service intervals or pre-mature failure. Turbulence also changes the way how the flow interacts with the turbine blades, affecting the efficiency of the turbines. All these uncertainties represent a commercial risk for tidal power plant developers.

Numerous laboratory or numerical studies have explored the effects of turbulence on the loading of the turbine blades, and a good summary of recent work on this topic is provided by Milne et al. (2016). However, these attempts can only provide limited results. Laboratory flumes are unable to recreate the extremely high Reynolds numbers (of order 10^{-8} or higher) found in actual tidal channels. Current attempts to deal with the challenge of turbulence are either computationally intensive (e.g. Large Eddy Simulation), or are based on linearized models that do not reflect important aspects of the underlying physics. Most importantly, the vertical structure of the turbulence—both in terms of the turbulent energy production and dissipation—depends on the local topography and oceanographic forcing conditions, and the structure of turbulence is not necessarily correlated with the vertical structure of the flow field (Stevens et al., 2012; McMillan et al., 2016). In the absence of actual field measurements of the turbulent flow, the inputs into laboratory or numerical simulations do not properly represent real-world conditions.

In order to understand, predict and model the unsteady interactions between turbine devices and turbulence requires the measurement of mean current speeds and the turbulent velocity fluctuations over a continuum of length scales ranging from those comparable to the turbine rotor diameter, down to scale similar to the chord length of the rotor blades. The larger scales mainly affect the turbine on a structural level, where the gusting and buffeting causes intermittent and differential loading of the turbine. The smaller scales can cause resonant vibrations and affect the efficiency of the turbine blade.

There is no single instrument capable of providing this coverage of length scales. The types of commercially available instruments can be broadly classified into two categories: acoustic and non-acoustic instruments. Acoustic instrumentation includes both acoustic Doppler current profilers (ADCP) and acoustic Doppler velocimeter (ADV) range of instruments; non-acoustic instrumentation includes velocity shear probes in a range of configurations.

The following section describes these instrumentation options and their relative advantages and shortcomings. Section 3 describes an integrated measurement system, *Nemo*, that utilizes both acoustic and non-acoustic sensors to measure flow turbulence in tidal channels. Section 4 describes two research and development projects, Turbulence in the Marine Environment (*TiME*) and In-Situ Turbulence Replication and Measurement (*InSTREAM*), which are aimed at testing instrumentation solutions and methods using both sensing technologies.

2. MEASUREMENT TECHNIQUES

2.1. Acoustic Methods

2.1.1. Acoustic Doppler Current Profilers (ADCP)

Many of the previous, and ongoing, resource assessments have ADCPs to assess the variability in the flow. Commercially available ADCP are relatively easy to deploy on suitable seafloor platforms (Figure 1). With the acoustic beams facing upward, the ADCPs readily provide vertical profiles of mean flow and second-order turbulence statistics spanning nearly the full water column. Due to high noise levels and the necessary assumption that the flow is statistically homogeneous and at steady state, standard ADCPs are incapable of measuring instantaneous 3-component turbulent velocities. The inertial subrange of the velocity fluctuations can be resolved for length scales larger than approximately 1 m (McMillan et al., 2016).

Despite these limitations, ADCPs are often the instrument of choice for several reasons. The ability to measure the flow remotely enables the characterization of the undisturbed flow throughout the water column. In addition, they can be deployed for long intervals of time (months to years), making it possible to assess the variability over a wide range of time scales. ADCPs can also be installed on moorings in the mid-water column, where they can face upward or downward, depending on the requirements, but motions of the mooring must be taken into account. Figure 1 shows a typical ADCP in various deployment configurations.

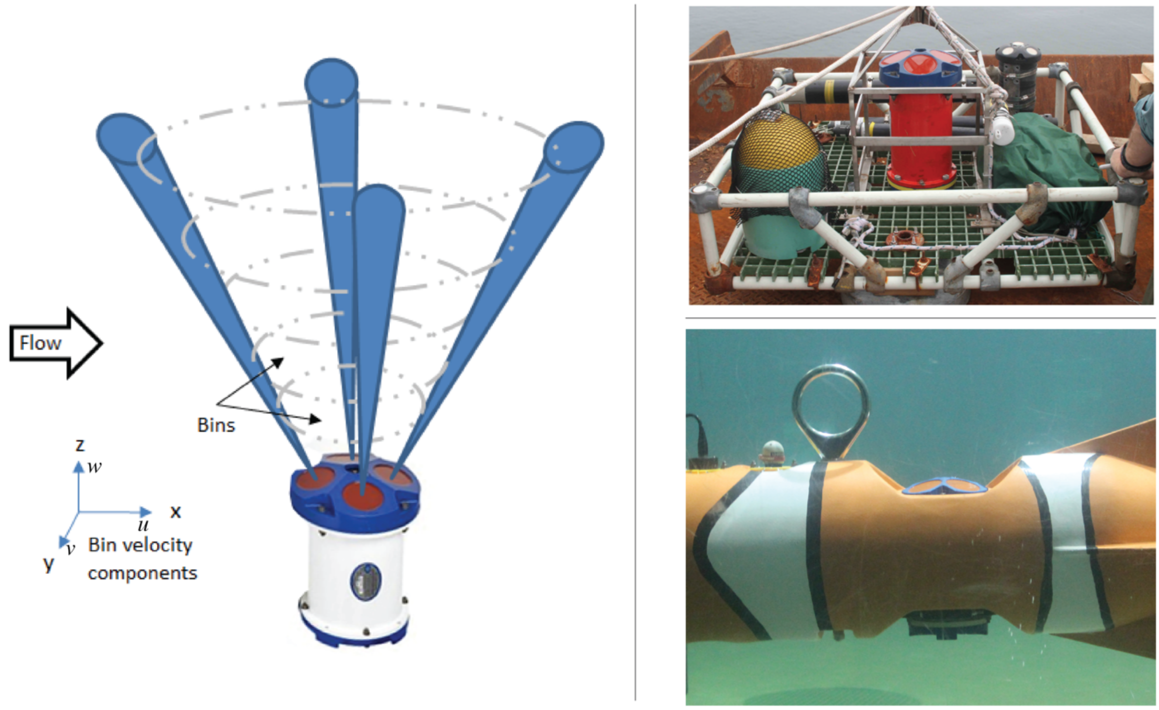

Figure 1: Left, schematic of a vertically oriented, bottom-mounted ADCP. Top-right, installation of an ADCP in a seabed platform and, bottom-right, on a moored float.

2.1.2. Acoustic Doppler Velocimeters (ADV)

The fundamental difference between the ADV and the ADCP is that the ADV samples a small volume of approximately 1 cm^3 using three (or sometimes four) convergent acoustic beams to derive three components u, v, w of velocity at a point at a relatively high temporal resolution (64 Hz or higher). This resolution is sufficient to provide a direct way of measuring turbulent Reynolds stresses $\overline{u'w'}$, $\overline{u'v'}$, $\overline{v'w'}$, or portions of the turbulent velocity spectrum in the inertial subrange. The ADV instruments are relatively small and are easily integrated into a variety of measurement platforms. Figure 2 shows an ADV mounted on a moored float.

Numerous field observations have shown that there is often a lack of particles in tidal channels, which restricts the usefulness of the ADV technique (Hay et al, 2013). The standard deviation and noise level of ADV measurements depend heavily on the presence of acoustic scatterers in water, which determine the instrument's signal to noise ratio. In the absence of scatterers more samples need to be averaged to achieve a reliable estimate of u, v, w. This lowers the effective sampling rate and, ultimately, the spatial resolution of the measurement. Furthermore, in very fast flows, when sampling at the typically ADV rate of 64 Hz, the spacing of individual samples is $U/64$ (where U is the mean flow speed). For speeds $U > 1$ m/s the spacing between samples exceeds the width of the sampling volume (which is approximately 1 cm). The ability of the ADV to resolve turbulence scales therefore varies significantly with the operating environment.

Figure 2: ADV integrated into the *Nemo* moored platform.

A related problem occurs laboratory facilities, where scatterers are added to the water to increase signal-to-noise ratio of the acoustic measurements. This is undesirable for two reasons: first, large amounts of the seeding material render the water opaque, inhibiting visual observations during the test; and second, the removal of the seeding material after the test is costly and time consuming because it requires flushing of filter systems, or possible drainage of the flume.

Nevertheless, ADVs have been used with success in tidal channels to measure mean flow and turbulent parameters (Milne et al., 2013; Thompson et al., 2012), and they are a very useful supplemental device for measuring turbulence.

2.2. Non-acoustic Methods

The velocity shear probe was developed in the 1960s in Canada and adapted in the early 1970s for use in the ocean (Osborn, 1974). Since then it has become the standard sensor for measuring oceanic turbulence. The shear probe is a non-acoustic sensor that is in direct contact with the water. The sensor deforms microscopically in response to a lift force that is created by the flow passing over the curved sensing tip (Figure 3). A piezo-ceramic element embedded in the tip transforms the deformation into an electrical signal that is directly related to the turbulent velocity fluctuations, shown as w in the figure. The sensing tip is approximately 1 cm long, which gives the probe the ability to measure velocity fluctuations at length scales between approximately several meters down to 1 cm, covering the inertial subrange to dissipation range of the turbulence velocity spectrum. Shear probes are typically deployed from free-falling profilers, gliders or AUVs, or mounted on floating platforms in the flow, such as the Nemo system discussed in the next section.

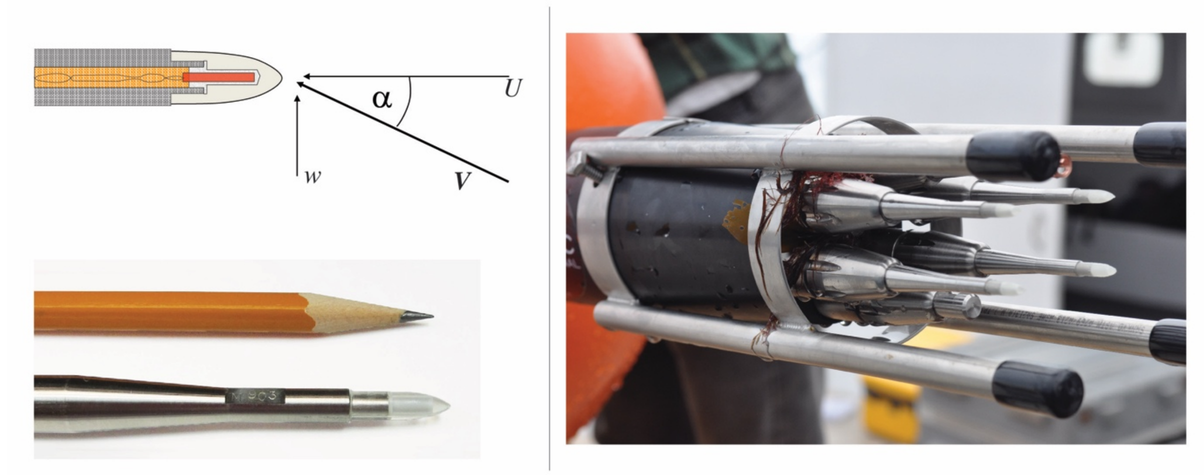

Figure 3: Left top, schematic of the shear probe showing the vector diagram of the flow. The probe travels through the water (or flow passes over the probe) with an axial speed U. Together with the cross flow component, w, this results in a flow velocity vector $\boldsymbol{V}$, which creates a lift force that is proportional to w. Due to its construction, the probe is only sensitive to the w component. Left bottom, sensing tip of the shear probe. Right, four shear probes (visible as the white tips) integrated into the nose section of the moored instrumentation flow, Nemo.

Shear probes have been used for measurements in tidal channels in Nova Scotia (McMillan et al. 2016) and Scotland (Lueck et al, 2015), and in New Zealand (Stevens et al., 2012), in both moored and in profiling configurations. When mounted on a vertical profiler and deployed from a surface vessel, it is possible to rapidly assess the turbulence characteristics of a site by conducting a series of profiles. As an example, Figure 4 shows the cross section of turbulent kinetic energy dissipation rate, ϵ, measured with a shear probe profiler in Islay Sound, Scotland (Lueck et al., 2016).

The advantage of the shear probe is that they have an extremely high signal to noise ratio and frequency response, independent of the presence of acoustic scatterers. This makes the probe also attractive for use in laboratory facilities. The disadvantage of the shear probe is that it can only measure cross-stream components of the flow and that it needs to be oriented axially into the main flow within a maximum angle of attack.

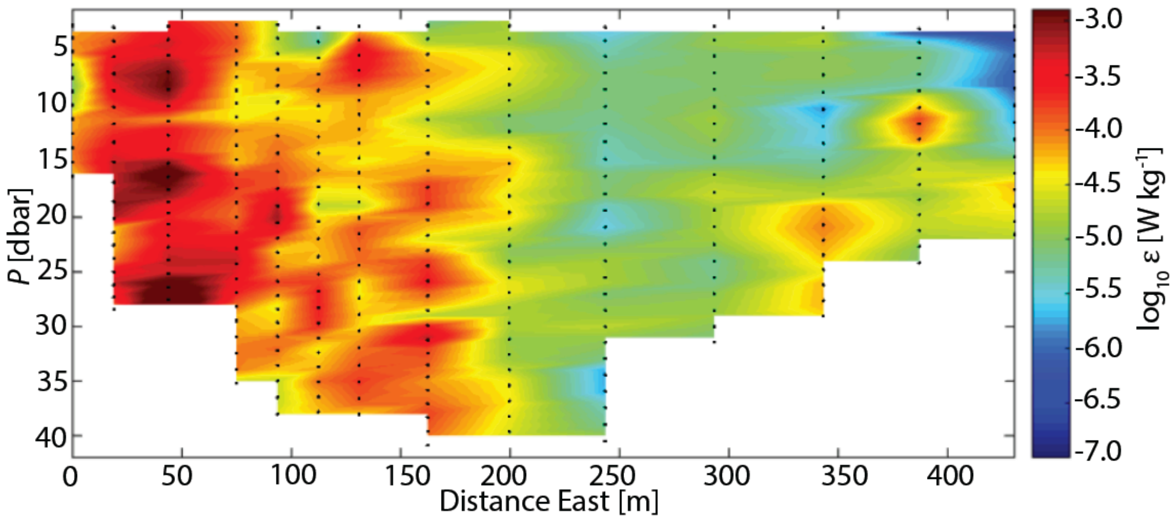

Figure 4: The cross-channel section of the rate of dissipation of kinetic energy, ϵ, measured with a shear probe profiler in Islay Sound during an ebb tide. The black dots indicate the location of individual profiles. Figure from Lueck et al. (2016).

3. THE NEMO FLOAT

A Canadian collaboration between Rockland Scientific and Nova Scotia's Dalhousie University lead to the development in 2013 of the Nemo floating platform for measuring turbulence in a tidal channel. Nemo combines non-acoustic and acoustic sensing technology and can be 'flown' at mid-depth in the water column to provide time series of turbulence at the hub height of a tidal turbine. Nemo is 4.5m long and is composed mostly of syntactic foam (Figure 5) with cut-outs to house various instrumentation components.

The Nemo system was successfully deployed in several tidal channels that are slated for tidal energy generation in Scotland (Islay Sound, Corryvreckan Sound, Inner Sound at Pentland Firth) and Nova Scotia, Canada (Minas Passage and Grand Passage). Flow speeds in these locations can reach 5 m/s. This environment represented significant challenges for the design of the mooring and the turbulence instrumentation. Data from a deployment in Islay Sound are described by Lueck et al. (2016).

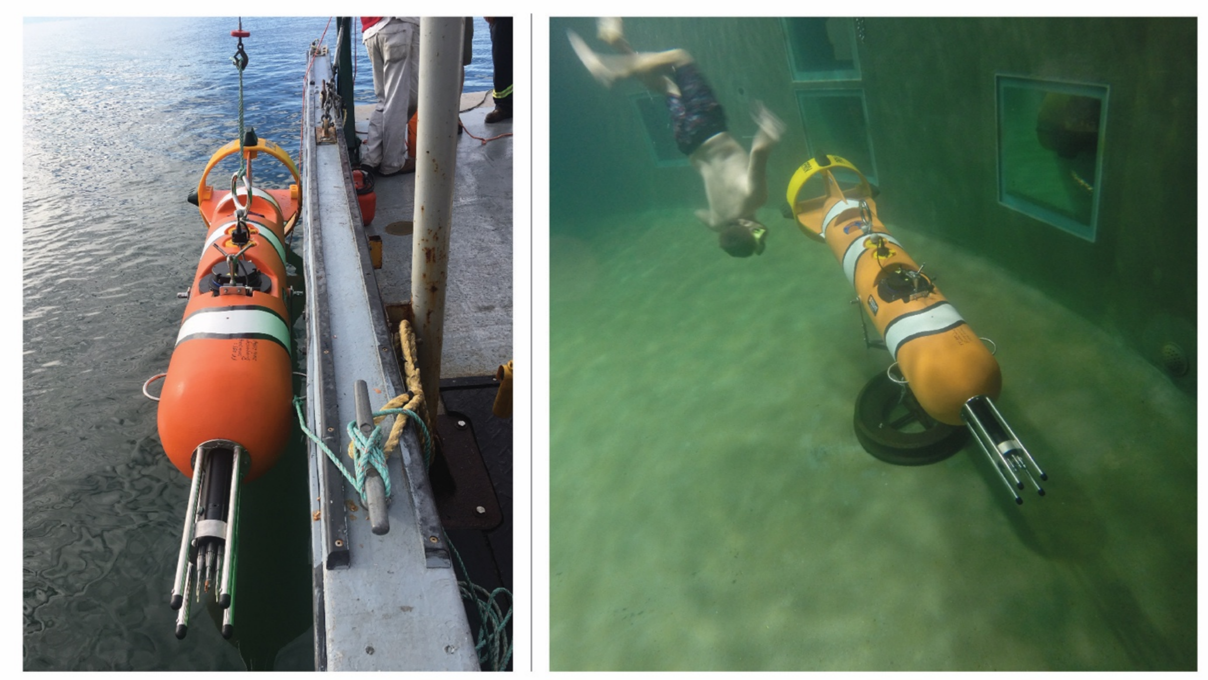

Figure 4: Left, the Nemo float configured with shear probes (in the nose section), ADV (at mid body), and upward pointing ADCP (rear body) prior to deployment in Minas Passage, Nova Scotia, as part of the *InSTREAM* project. Right, during ballasting tests at Dalhousie University.

4. PERTINENT RESEARCH PROJECTS

Two extensive, multi-national research and development systematically address the instrumentation and methodology requirements for measuring turbulence in tidal channels. The outcomes from these projects represent a comprehensive body of knowledge that informs the tidal energy industry, as well as academia, on the best practices for reliably characterizing marine turbulence in these extreme environments.

4.1. THE *InSTREAM* PROJECT

By combining available sensor technology, the goals of the In-situ Turbulence Replication Evaluation And Measurement *(InSTREAM*) project are to develop a set of sensors and methods that can be used at tidal energy sites as well as laboratory-scale simulators, and measure time-averaged turbulence quantities as well as turbulent intermittency. The sensor technology is designed to provide turbulent flow measurements that are directly translatable between the laboratory and the field environments.

A research consortium comprising six commercial and academic entities in the UK and Canada was formed to carry out the three-year research project, which is currently in its second year. The consortium consists of Rockland Scientific in Victoria, BC in partnership with Dalhousie University and Black Rock Tidal Power in Nova Scotia, along with UK-based FloWave Ocean Energy Research Facility, European Marine Energy Centre (EMEC), and Ocean Array Systems Ltd.

Instrument systems, comprising non-acoustic and acoustic sensors will be tested and installed at three locations during the 2016 experimental season. The first installation is at the FloWave Ocean Simulator in Edinburgh, UK, to test and validate the laboratory configuration of the shear probe measurement system (Figure 6). Deployments of the Nemo float are then carried out at two field sites: at EMEC in Scottish Orkney Islands and at Minas Passage in the upper Bay of Fundy in Nova Scotia, Canada. The measurements at these sites will be used to provide a translation between the effects of turbulence on turbines at model scale in FloWave and the effects likely to manifest at full scale. Furthermore, the extended time series data of high-resolution turbulence captured with shear probes are analyzed to refine statistical models of turbulence intermittency.

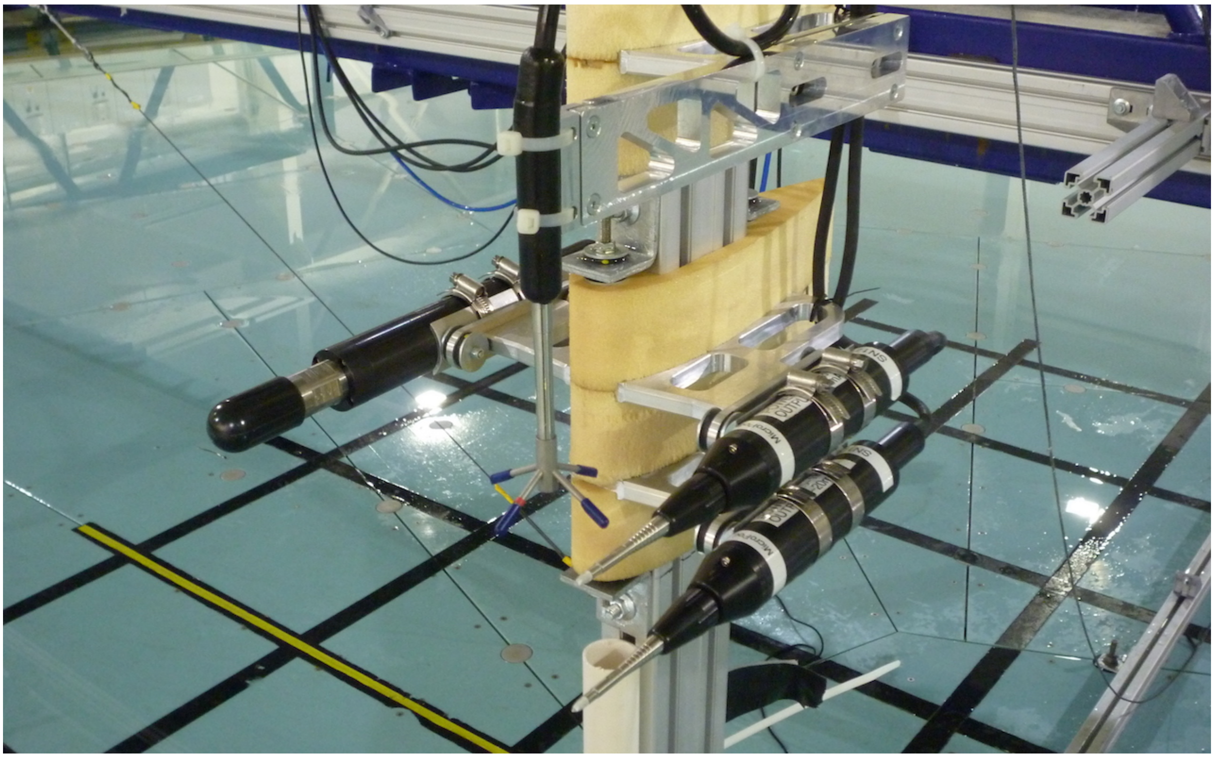

Figure 6: Laboratory setup in the Flowave facility, showing two shear probes (front-centre), an ADV (centre-left), and an electromagnet flow sensor (left).

4.2. Turbulence in the Marine Environment (*TiME*)

The *TiME* project, concluded in 2015, has the main objective to develop a framework for measuring, classifying and predicting the effect of turbulence on resource assessment, device design/operation and array yield by using a combination of modelling, field measurement and theoretical analysis. The project collected turbulence data with the Nemo system (and other bottom-mounted instrumentation) at two commercially relevant Scottish tidal power sites: the Sound of Jura and the Inner Sound at Pentland Firth.

The results from the *TiME* project have been disseminated in the form of three guidance documents, which provide a detailed and comprehensive summary of the state-of-the-art of the available instrumentation and methods. The first of these documents describes the currently commercially available instruments for measurement of marine turbulence, their selection for a particular purpose and their limitations. The document also provides technical details on instrument configuration for optimal turbulence investigation, recommendations for survey planning and marine operations, as well as guidance for data management and quality control. Part 2 of the documents describes data processing techniques, and Part 3 addresses the effect of turbulence on tidal stream turbines and arrays. The guidance documents are referenced by Clark et al. (2015).

5. CONCLUDING REMARKS

Combining the non-acoustic and acoustic sensing technologies described in Section 2 makes it possible to characterize the entire turbulent velocity spectrum pertinent to tidal energy generation. The ADCPs have the ability to remotely measure large scale turbulent shear an turbulent stresses, on length scales associated with the rotor diameter (~10 m). Shear probes provide a measure of the high frequency/small wavenumber portion of the turbulent velocities on scales between the blade width and the blade length of the rotor (approximately several centimeters to several metres). ADVs provide a point measurement of the mean and fluctuating components of the flow on the interleaving length scales (~1 to 10 m).

The Nemo float described in Section 3 combines these sensing technologies into a single instrumentation package that has been successfully deployed in several tidal channels. It can measure the full spectrum of turbulent flow measurements in currents exceeding 5 m/s.

Two R&D projects, *Time* and *InSTREAM*, have systematically explored and tested the available acoustic and non-acoustic sensing technology for use in the field and in laboratory settings.

Future work will be directed at exploiting the data products provided by the presented sensing technologies and methodologies. The resulting improved to make useful measurements, combined the ability to model turbulence effects based on those data, will provide meaningful information to marine surveyors and turbine device developers.

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BIOGRAPHICAL NOTES

Dr. Fabian Wolk has extensive scientific and technical expertise in oceanographic sensing systems, specializing in the measurement of turbulence and micro-scale parameters in marine environments. As President and Co-Founder of Rockland Scientific, he has accumulated more than 20 years of business experience in delivering instrumentation solutions for the measurement of turbulence in oceans, lakes, and rivers. Dr. Wolk also serves on the Board of Directors of Marine Renewables Canada and on the Canadian subcommittee to IEC/TC114 for the development of international standards relating to tidal resource assessment.

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