The InSTREAM Project – Characterizing and Simulating Turbulence from a Test Tank to the Ocean

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Abstract- To mitigate the risk and uncertainty associated with turbulent flows in tidal channels, developers often use tank experiments and numerical simulations to assess the power and loading performance of a turbine. However, it remains unclear if these controlled flows can be accurately scaled up to represent the natural turbulence present in tidal channels. The difficulty in translating between model, tank and full scale turbulent effects motivated the In-Situ Turbulence Replication, Evaluation And Measurement (InSTREAM) project. The three-year project included the development of a sensor system that combined acoustic (Doppler), and non-acoustic (electro-magnetic and shear probe) technology to create a system that could be used in both laboratory and field applications. The system was successfully deployed at the FloWave Ocean Energy Research Facility and in the Minas Passage, Bay of Fundy. The measurements from both the lab and the field were then used to perform numerical simulations of turbine performance. A direct comparison between the "tank" and "ocean" conditions was obtained by implementing a scaling method to translate the length scales between the two flow regimes. The results – from both the measurements and the simulations – highlight that there are significant differences in the turbulence characteristics between the tank and the field. In particular, the larger relative size (by a factor of three) of the 3D eddies present in the ocean generated more complex wake dynamics, and lower power and thrust coefficients.

Keywords- measurements, numerical simulations, tank testing, tidal site characterization, turbulence

I. INTRODUCTION

The strong flows through tidal passages are – by nature – extremely turbulent. The associated velocity fluctuations are chaotic and unsteady and, hence, affect the reliability and efficiency of energy extraction. In addition, the turbulent wakes downstream of turbines can complicate the efficiency of energy capture at array installations, and the wake may have environmental effects (scouring).

Ideally, it would be possible to predict the effect of turbulence on turbines and turbine arrays before the devices "get wet" (i.e. are installed in the ocean). Numerical simulations of tidal flows can be used to improve turbine design, estimate loading forces, and determine optimal turbine placement [1]. Numerical models are typically initialized and validated using measurements from laboratory experiments [2], however, the properties of the turbulence in a tank are arguably different than those in a tidal channel due to the differing scales of the turbulent structures present in the flows. The influence of tank vs. ocean turbulent flow regimes on model results is not well understood and is, therefore, a significant source of uncertainty in simulations of turbine performance.

The predictability of a turbulent tidal flow is further complicated by its natural complexity. A "full-scale" flow in a tidal channel has velocity fluctuations that occur across a large range of scales. Large velocity fluctuations have time scales on the order of hours that cannot be replicated in standard turbine models, whereas small, device-scale, fluctuations occur over time scales of seconds and are inherently unpredictable. Furthermore, the velocity fluctuations are localized in space and vary significantly over scales of ~100 m within any given tidal channel. Measuring the full range of scales using a single instrument is technologically impossible, and hence, a combination of sensors needs to be used to characterize the flow at a single site.

The In-Situ Turbulence Replication, Evaluation And Measurement (InSTREAM) project attempted to address the difficulties associated with (1) measuring the full spectral range of turbulent motions, and (2) translating between model and full scale turbulent effects. The three-year project, which was completed in early 2018, was carried out by a research consortium comprising six commercial and academic entities in the UK and Canada. The project was co-funded by the Offshore Energy Research Association and InnovateUK. The Government of Canada (NRC-IRAP) provided additional funding to the Canadian partners. In Europe, the project was given the prestigious EUREKA designation.

The objectives of the InSTREAM project were: (1) to measure, characterize and simulate turbulence from test tank to the ocean, (2) to develop a set of sensors and methods that can be used at both tidal energy sites and in laboratory tanks, (3) to determine the differences between the turbulent properties in a laboratory tank and at tidal sites, and (4) to identify and understand the impact of these differences in numerical simulations of tidal turbines. These objectives were achieved by measuring and comparing the full spectrum of turbulence in both a test tank and a tidal channel, and then simulating both flow regimes in numerical simulations of tidal turbines.

This paper summarizes the methodology implemented to achieve these objectives and highlights the key findings and outcomes. For a more in-depth analysis of the scientific results, the reader is referred to [3].

II. METHODOLOGY

The InSTREAM project included the development of a sensor system that combined standard flow measurement technology (i.e. acoustic) with non-acoustic measurement technology (i.e. shear probes) to create a system that is useful for turbulence observations in both laboratory and field applications. The system was deployed at (1) the FloWave Ocean Energy Test Facility in Edinburgh to test and validate the laboratory configuration, and (2) at two sites in the Minas Passage to characterize the turbulence and its spatial variability within an energetic tidal channel.

A. Tank Measurements

Measurements were carried out at FloWave in early 2016. The FloWave test tank is a 1:20 scale experimental facility for ocean energy research. The tank is 25 m in diameter and 2 m deep, corresponding to a full-scale depth of 40 m. The symmetrical, circular facility has 28 current generating impellers and 168 wave making paddles arranged around the circumference which allows waves and currents to be generated with any relative direction. For the purposes of this experiment, the FloWave tank was set to generate a horizontal current with a width of approximately 6 m. Flow speeds of 0.6 m/s, 0.8 m/s, 1.0m/s and 1.2 m/s were used, allowing different turbulent regimes to be characterized.

Data were collected using a suite of instruments (Figure 1) that included a MicroPod-EM, two MicroPod-Shear and an acoustic Doppler velocimeter (ADV). The MicroPod-EM is a modular one-dimensional electromagnetic current sensor that measures the mean flow velocity. The MicroPod-Shear is a modular instrument package containing a single shear probe which measures the cross-stream variance (i.e. the turbulent fluctuations) at a sample rate of 2000 Hz. Both of these MicroPod sensors are solid state devices that do not rely on acoustics and sound scatterers, so they will work in very clean water conditions that are often desired in test tanks. The MicroPod measurements were corroborated using the ADV which obtained three-dimensional velocity measurements at a sample rate of 100 Hz. The ADV probes were mounted such that their measurement volume was approximately 50 mm upstream of the MicroPod-Shear sensors.

Tank experiments were conducted to investigate both spatial and temporal characteristics of the current. The objectives were to both characterize the turbulent regimes in the tank and to generate a flow regime that would be comparable to the natural turbulence levels present in tidal channels.

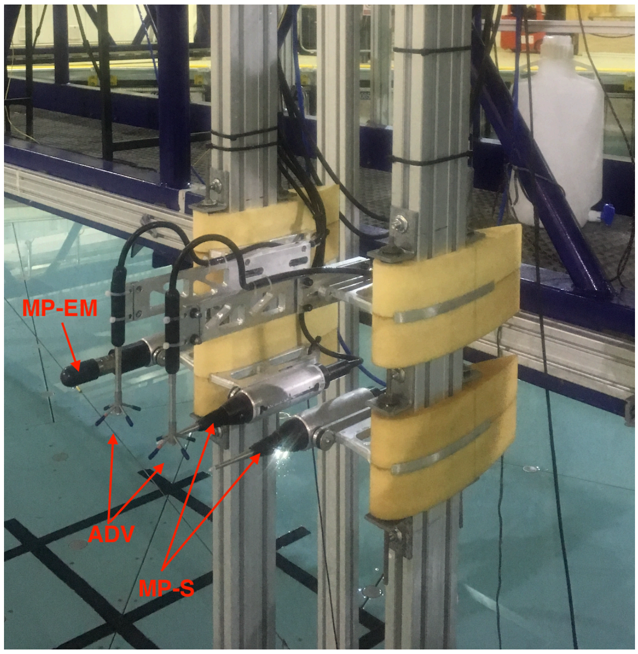

Figure 1: The experimental setup in FloWave included two acoustic Doppler velocimeters (ADV), two MicroPod-Shear (MP-S) units, and one MicroPod-Electromagnetic (MP-EM) current meter.

B. Field Measurements

A two-week field campaign was successfully carried out at two locations in the Minas Passage in August 2017. The two sites were separated by 200 m and were approximately 2 km west of Black Rock Island. The mean water depth at both sites was approximately 55 m and the flow speed reached 4 m/s near the surface [3].

The data were collected using two moored instrument systems (Figure 2), referred to as “Nemo East” and “Nemo West”. The Nemo floats have torpedo shaped bodies and are moored to the sea floor through an acoustic release. The floats are free to swivel a full 360 degrees, allowing for measurements in all flow directions. In addition, the bridle and axle that connect the mooring line to the float body allow the floats to remain horizontal despite the high drag that causes significant “blow-down” of the buoy [4].

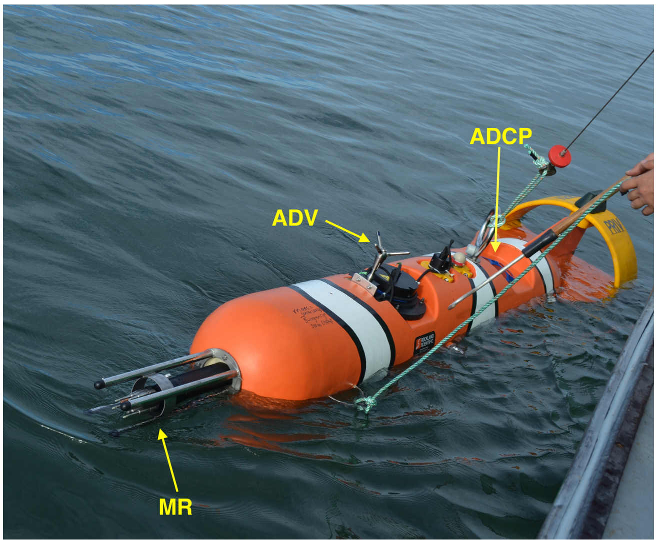

Figure 2 : The Nemo-West buoy being lowered into the Minas Passage. The instrumentation includes a MicroRider (MR), an acoustic Doppler velocimeter (ADV) and an acoustic Doppler current profiler (ADCP).

The Nemo floats are self-contained systems with batteries, instruments and data-logging capabilities. Each float was equipped with a MicroRider containing four shear probes, one thermistor, a pressure transducer, a two-axis precision inclinometer, a 6DOF gyro, and a magnetometer. An ADV and an upward looking acoustic Doppler current profiler (ADCP) were also installed. The shear probes on the MicroRider were sampled at 2048 Hz allowing for a measurement of the turbulent fluctuations, whereas the ADV and ADCP were used to estimate the mean flow speed at and above the Nemo buoy. The sample rates were 16 Hz for the ADV and 0.5 Hz for the ADCP.

An additional field campaign was carried out in the Fall of Warness; however, the combination of a software bug and the simultaneous failure of a shore cable prevented the collection of useful scientific data.

C. Numerical Simulations

Numerical simulations were carried out by Octue Ltd (formerly known as Ocean Array Systems Ltd.) using the method outlined in [5]. A model of the Schottel Hydro turbine was used as the base device for the simulations. For the simulations conducted as part of the InSTREAM project no blade deflection and no platform motion were accounted for. The numerical simulations were performed with a smooth bottom and level sea surface. The impact of the turbulent flows on both single turbines and turbine arrays were analyzed. The power and thrust coefficients were computed and the wake dynamics were assessed.

Turbulent inflow conditions were generated using the Mann method [6] using the integral length scales determined from the measurements in the Minas Passage and in FloWave. The tank measurements were linearly scaled up, ensuring that the nondimensional ratio of the integral length scale, l, to the turbine tip radius, R, was constant. Mathematically,

$$\frac{l_{model}}{R_{model}} = \frac{l_{tank}}{R_{tank}} = \frac{l_{ocean}}{R_{ocean}},$$

which ensures that all parameters are held constant between the full-scale ocean simulation and the tank simulation. This scaling is inherently simplistic, and doesn't take into account the non-linear Reynolds number effects that arise when translating between a small-scale test tank and the large-scale ocean. However, it is consistent with the outcome of the TiME project, which found that turbulent length scale had significant influence on the loading forces and the structure of the turbulent wake [7].

The simulation of the ocean conditions used 19.3 m and 2 m for l_{model} and R_{model}, respectively, which correspond to the measured length scale in the Minas Passage and the tip radius of the full-scale Schottal turbine. For the simulation of the tank conditions (on the same 2 m turbine), a length scale of l_{model} = 5.6 m was used, which is scaled from the tank values of l_{tank} = 0.7 m and R_{tank} = 0.25 m.

The mean flow was represented by a logarithmic velocity profile based on a measured average flow speed of 1.2 m/s at the height of the Nemo buoy. The velocity profile was set with a linearly scaled reference height, which slightly alters the relative shape of the profile. To avoid bias, the power-weighted, area-averaged mass flux through the turbine disc in the both the tank and ocean simulations were held constant to ensure that the only effect on the power coefficients must be caused by the turbulence, as opposed to the velocity shear.

III. RESULTS

The measurements and simulations conducted as part of the InSTREAM project were successful. The following subsections describe the results of each of the project components with further discussion and comparison summarized in Section IV.

A. Tank Measurements

The measurements collected at FloWave were of overwhelming good quality and quantity. System testing showed excellent agreement between the ADV and the MicroPod-EM when they were located closely together on the mounting frame. As the separation increased, they did not correlate as well. The turbulence data collected with the MicroPod-Shear agreed well with the ADV. In addition, the shear data could be used to estimate the flow velocities with good coherency and correlation to the ADV.

A direct comparison of the velocity spectra measured by the shear probes and the ADV reveals that the measurements are in excellent agreement (Figure 3). The shear probe measurements (yellow) show an inertial subrange (where $\phi \sim k^{-5/3}$) spanning wavenumbers from 2 to 50 cpm. At low wavenumbers the spectral level (i.e. the variance) decreases because the eddies are constrained to 1 m scales by the limited depth of the tank. At high wavenumbers viscosity acts on the small eddies and removes their variance in the form of heat. The velocity spectrum from the ADV closely tracks the shear probe measurements, except that the maximum resolvable wavenumber was ~30 cpm due to the sample rate of 100 Hz. There may also be some aliasing present in the ADV measurements.

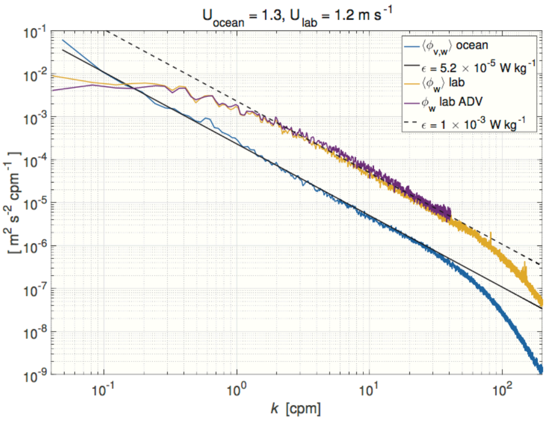

Figure 3 : Wavenumber spectra of velocity fluctuations measured at the Minas Passage site (blue) and at the FloWave facility (yellow, maroon). The solid and dashed black lines represent the $k^{-5/3}$ dependence with the ε values specified in the legend.

B. Field Measurements

The two Nemo buoys performed well and yielded high quality measurements of both the mean and turbulent flow conditions. Both buoys experienced significant blowdown – i.e. the buoy was closer to the bottom during strong flows than at slack water – that was well predicted by the force balance between drag and buoyancy [3,8].

The velocity profiles above the Nemo buoys were calculated from the upward looking ADCPs. The profiles between the two floats were comparable where the two instrument ranges overlapped [3]. The lowest portions of the profiles were logarithmic in shape and fits to the law-of-the-wall were used to determine the drag coefficients. Values of $C_d = 8.7x10^{-3}$ and $4.0x10^{-3}$ were estimated for the flood and ebb tides, respectively, exhibiting ebb-flood asymmetry that has also been observed at other Bay of Fundy tidal sites [9].

The characterization of the turbulent flow was done using the measurements collected by the shear probes (on the MicroRider) and the ADCP. The dissipation rate of turbulent kinetic energy, ε, was used as a metric for the intensity of the turbulence. It was estimated directly from the spectra of the shear probe measurements (Figure 3, blue line) and using a second order structure function method applied to the diverging beam ADCP data [10]. The ε estimates agreed well between the two instrument types. As expected, the dissipation rates increased with increasing mean speed on both the flood and ebb tides, and have a dependence on the cube of the mean flow speed (i.e. $\varepsilon \sim U^3$), which is the scaling expected for boundary layer flows [3]. Over a tidal cycle, the dissipation rates varied by a factor of 10^4, from 10^{-7} W/kg during slack flows to 10^{-3} W/kg during peak flood conditions [3].

The turbulence measurements were also used to estimate the integral length scale of the largest eddies and profiles of the Reynolds stresses. These parameters are important to the overall characterization of a site, but further discussion is beyond the scope of this paper.

C. Numerical Simulations

The numerical simulations of the tank vs. ocean flow regimes show significant differences in the wake evolution, power coefficients and thrust coefficients. For the simulation of a single turbine, the average power coefficient for the tank conditions was approximately $C_p = 0.9$, whereas the value was approximately 0.7 for the ocean simulation. The effect on the magnitude of the thrust coefficient was similar – a value of $C_T = -0.2$ was observed for the tank simulation and -0.1 for the ocean simulation.

The wake dynamics of the single turbine are also affected by the factor of 3 difference in the relative size of the integral length scale (i.e. 19.3 m for the ocean simulation and 5.6 m for the tank simulation). In the tank simulation, the length scales are comparable to the turbine size (2 m) and the turbine wake breaks down quickly. On the other hand, in the ocean simulation the turbulent kinetic energy exists at scales much longer than the turbine diameter, leading to a more prominent wake that meanders significantly downstream of the turbine site. The behaviour is clearly visible in a video available online [11].

Similar patterns are observed in the simulation of a three-turbine array [12]. The turbines were spaced at intervals of 8 turbine diameters in the streamwise direction and offset by two turbine diameters in the lateral direction. The differences in the wake dynamics between the tank vs. ocean simulations cause significant differences in the flow conditions experienced at the downstream turbines (Figure 4). For the ocean conditions, the meandering wakes interact and create a highly unpredictable flow regime, whereas for the tank conditions, the turbine wake breaks down before significant interaction can occur.

IV. DISCUSSION

Measurements at FloWave and in the Minas Passage show that there is a significant difference between the velocity

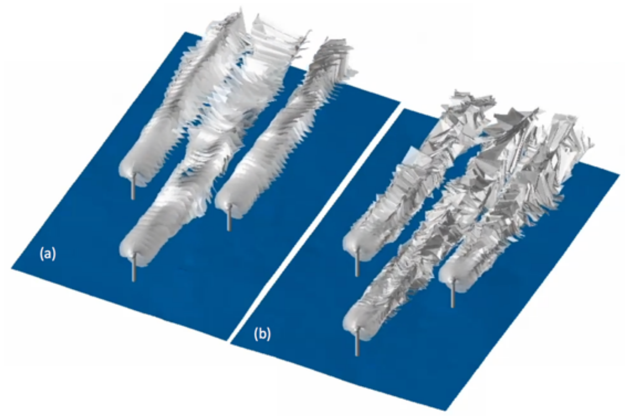

Figure 4 : Snapshots from numerical simulations of realistic tidal flow past a turbine array. Inputs were chosen to best represent (a) field conditions and (b) laboratory conditions.

fluctuations observed in a tidal channel and the turbulence that can be generated in a laboratory setting. The discrepancy arises from the difference in size of the largest three-dimensional eddies. In an unstratified flow – like those present in tidal channels – the largest eddies are scaled by the distance to the nearest boundary, such as the bottom or the free surface. Because the Nemo buoys were situated between 7 and 15 m above the bottom during strong flows, an eddy size of ~10 m is expected. On the other hand, the FloWave tank is 2 m deep, so that largest eddy size at mid-depth is ~1 m.

These differences in scale are apparent in the velocity spectra in Figure 3. The shear probe data collected in the Minas Passage (blue line) shows an inertial subrange extending to wavenumbers smaller than 0.05 cpm, which corresponds to a wavelength of 20 m (or an eddy size of ~10 m). On the other hand, the spectra measured by both the shear probes and the ADV in FloWave (yellow and maroon lines) roll off at wavenumbers below 1 cpm because eddies smaller than 0.5 m are suppressed by the rigid boundaries.

These results suggest that the measurements collected in a laboratory facility replicate the high wavenumber portion of the spectrum only. Measurements for lower wavenumbers must be carefully scaled to account for the under-representation of the largest scales, which are likely very important for assessing the hydrodynamic loading forces on a turbine. As shown by the numerical simulations, the omission of these large length scales leads to higher predictions of the power and thrust coefficients and simpler – but likely unrealistic – wake dynamics.

V. CONCLUSION

The InSTREAM project has made a significant contribution to addressing the concerns regarding turbulence at tidal energy sites. The key outcomes of the project are as follows:

- A sensor system has been developed that overcomes the shortcomings of existing measurement technology to reliably and consistently resolve the full range of turbulent scales, both in the laboratory and in a tidal channel.
- A wealth of high quality turbulent flow data were collected in both FloWave and the Minas Passage that has the potential to be used in future studies. The continued analysis of the data will inform scientific and engineering work aimed at understanding the impact of turbulence on tidal energy converters, as well as, describing and understanding site specific flow conditions.
- A linear scaling was developed that enables tank measurements to be scaled up to "real-world" ocean conditions (and vice versa). This scaling greatly increases the usefulness of tank testing and numerical modeling, and can be reproduced for other test tanks. It also allows site-specific field measurements to be translated to tank experiments, enabling numerical models (validated by tank experiments) to be used for reliable and realistic estimation of turbine and array performance.
- A direct comparison of numerical simulations of tank versus ocean turbulent flow regimes revealed significant differences in the wake dynamics, and the predicted power and thrust coefficients. The relative size of the three-dimensional eddies observed in the field were about 3 times larger than those generated in the tank, which – as revealed by the numerical simulations – yields a more meandering wake and a slower breakdown of the turbulent structures. This key result highlights the difficulty in simply scaling up tank experiments and numerical simulations to real tidal channels.

Moving forward, the success of the InSTREAM project will provide developers and manufacturers with the ability to evaluate both the turbulent flow at tidal sites and turbine designs at model scale and full scale. The results from this applied research project address technical challenges that ultimately reduce uncertainties in site design and yield assessments, which will lead to improved cost structure and access to financing through the reduction of economic risk.

ACKNOWLEDGMENT

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REFERENCES

[1] S.R. Alexander and P.E. Hamlington (2015). "Analysis of turbulent bending moments in tidal current

boundary layers". *Journal of Renewable and Sustainable Energy,* Vol. 7, 063118.
[2] Q. Hu, Y. Li, Y. Di, J. Chen (2017). "A large-eddy simulation study of horizontal axis tidal turbine in different inflow conditions". *Journal of Renewable and Sustainable Energy,* Vol. 9, 064501.
[3] T. H. E. Clark, R. G. Lueck, A. E. Hay, T. Davey, P. Stern, R. M. Horwitz, N. Pearson (2017). "InSTREAM: Measurement, Characterisation and Simulation of Turbulence from Test Tank to Ocean". *Proc. European Wave and Tidal Energy Conference.* Cork, Ireland. 10 pp.
[4] J. M. McMillan, A. E. Hay, R. G. Lueck, F. Wolk (2016). "Rates of dissipation of turbulent kinetic energy in a high Reynolds number tidal channel". *Journal of Atmosphere and Oceanic Technology.* Vol. 33, 817–837.
[5] T. H. E. Clark (2015). "Turbulence in marine environments (TiME): A framework for understanding turbulence and its effects on tidal devices". *Proc. European Wave and Tidal Energy Conference.* Nantes, France. 10 pp.
[6] J. Mann (1998). "Wind field simulation". *Probabilistic Engineering Mechanics*, Vol. 13, 269–282.
[7] T. H. E. Clark, T. Roc, S. Fisher, N. Minns (2015). "TiME Report Part 3: Turbulence and turbulent effects in turbine array engineering". Document no. MRCF-TiME-KS10. Marine Renewables Commercialization Fund, Scotland, 153 pp.
[8] R. M. Horwitz and A. E. Hay (2017). "Turbulence dissipation rates from horizontal velocity profiles at mid-depth in fast tidal flows". *Renewable Energy.* Vol. 14, pp. 283–296.
[9] A. E. Hay, J. M. McMillan, R. Cheel, D. J. Schillinger (2013). Turbulence and drag in a high Reynolds number tidal passage targeted for in-stream tidal power. *Proc. Oceans 2013*, San Diego, California, IEEE, 10 pp.
[10] J. M. McMillan and A. E. Hay (2017). "Spectral and structure function estimates of turbulence dissipation rates in a high-flow tidal channel using broadband ADCPs". *Journal of Atmosphere and Oceanic Technology.* Vol. 34, 5–20.
[11] T. Clark. "InSTREAM Video Top". *Vimeo, 29 Jan 2018,* https://vimeo.com/253207151.
[12] T. Clark. "video_3d_array_instream". *Vimeo, 29 Jan 2018,* https://vimeo.com/253204915 (Simulation 2, Turbine Array)

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