# Supergen Flex Fund project: Flow measurement for accurate tidal turbine design

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**Summary**

An unsteady pressure probe, the Barnacle, has been developed for accurate, low-cost turbulence measurements in tidal channels. During the Supergen Flex Fund project, the Barnacle was developed from a laboratory prototype to a marine device. The Barnacle was then tested alongside a conventional Acoustic Doppler Velocimeter (ADV) in a water tunnel at the University of Bath and in Strangford Narrows. Overall, the Barnacle gives good agreement with the ADV, and has a lower noise floor. In the water tunnel, we found that the Barnacle gave good mean flow data and resolved fluctuations even at mean speeds of 0.2 m/s. The data from Strangford Narrows showed that the Barnacle can resolves the same flow features as an ADV, including wind-induced surface waves, and has a lower noise floor.

**Introduction**

Tidal turbines operate in a hostile environment—high turbulence levels, waves, and large-scale unsteadiness from geographical features combine to generate large fluctuating loads on the turbine blades. Even small errors in unsteady load predictions at the design stage can lead to large reductions in the fatigue life of components. To compound matters, flow conditions can vary considerably even within one site. This means that tidal turbine designers need accurate steady and unsteady flow data across all parts of every potential installation site.

The usual device for measuring tidal flows is the Acoustic Doppler Current Profiler (ADCP), which is chosen for its ease of use—especially the fact that one seabed-mounted device can scan across the full depth of the channel. However, it has been shown in previous work by Guion and Young [1] that a standard ADCP can only capture relatively low-frequency flow features, and so miss some of the eddies that are most damaging to a tidal turbine. Milne et al [2] have suggested that Acoustic Doppler velocimeters (ADVs) could be used in place of ADCPs as they can capture higher frequency disturbances. However, they are less robust than ADCPs and take measurements at a single location, meaning that multiple devices are required to give information about flow variation with depth. Furthermore, both devices are too expensive to deploy at more than a few locations across a site.

There is, therefore, a need for a low-cost, easily deployable device that can capture unsteady velocity fluctuations. The use of multihole pressure probes is commonplace in aerospace research. For applications where space constraints are not too onerous, fast-response versions have been developed with the sensing components built into the probe head – most recently by Duquesne et al. [3,4] for small-scale water pumps. The major difference between their work and tidal flows is the background hydrostatic pressure, which is negligible in a small water pump, but will be up to two orders of magnitude larger than the dynamic pressure in a typical tidal channel. The hydrostatic pressure at depth in a tidal channel therefore dwarfs any changes in pressure due to unsteady flow passing over the sensors.

Young et al. [5] have developed a probe which uses differential pressure measurements to overcome the issue of high hydrostatic pressure, and tested it in a flume tank during a previous EPSRC project. During this Flex Fund project, the probe has been developed from a laboratory prototype to a robust device that can withstand the marine environment. Benchmarking tests at Strangford Narrows have also been undertaken. This report will describe the principle of operation of the Barnacle probe and show key results from the benchmarking tests. Finally, future directions for this research will be discussed.

**Principle of operation**

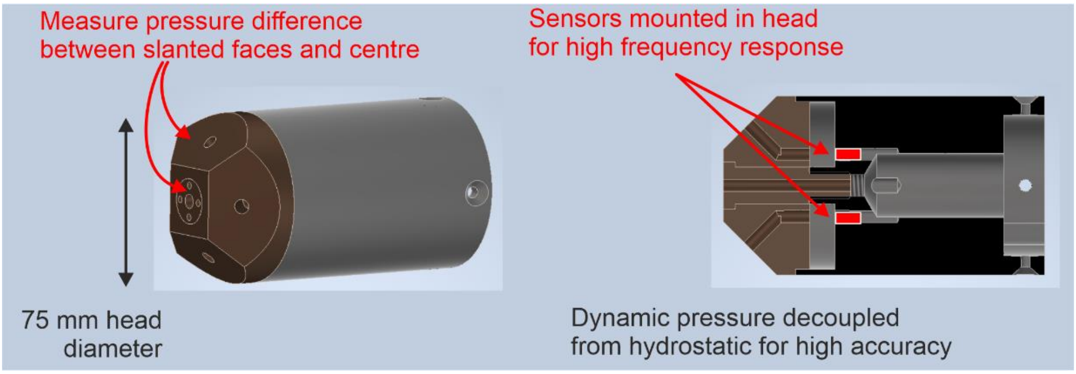


***Figure 1: Principle of operation of the Barnacle probe***

The principle of operation of the Barnacle probe is shown in Fig. 1. If the probe is aligned with the flow, the pressure on each of the four slanted faces will be equal, and the centre hole will register the stagnation pressure of the flow. If the flow is at an angle to the probe, then there will be a pressure difference between the slanted faces, and the centre hole will measure a lower pressure than the stagnation pressure.

By calibrating the probe in a known flow, a relationship can be found between the pressure difference on the slanted faces and the direction of the flow. Similarly, the flow velocity can be found from the difference between the pressure on the slanted faces and that registered by the centre hole. For more information on the calibration of five-hole probes, see [6-10]. At this point it should be noted that the significantly larger size of the Barnacle compared with aerospace probes gives two advantages:

1. The manufacturing tolerances are negligible compared with the size of the slanted faces. This means that the geometric aspect of the calibration coefficients will be negligible, and every probe should have the same coefficients (once any differences in the performance of the pressure transducers have been accounted for in the calibration from voltage to pressure).
2. The larger size of the probe means that the pressure transducers can be mounted in the head, which means that the unsteady component of the flow can be captured as well as the time average.

For further discussion of the principles of operation and the key changes from wind tunnel tests to marine measurements see Young et al [5].

**Water tunnel tests**

Tests were undertaken in the water tunnel in the Dept. of Mechanical Engineering at the University of Bath in December 2020 and July 2021. This facility is a short flume with glass sides and bottom, with a section of about 0.5 m width and 0.5 m depth from the free surface. It is designed to create very uniform flow in the working section with minimal boundary layer thickness at the walls and a low turbulence intensity, and it is used primarily for PIV velocimetry around physical models. No PIV was used in these tests, however the PIV seeding particles (neutrally-buoyant glass spheres) gave a good signal for an Acoustic Doppler Velocimeter (ADV), which was used as an independent measurement of upstream water velocity. The flow velocity can be varied from 0.2 m/s to 0.5 m/s.

The Barnacle probe was installed in the tunnel and the output voltage signals were measured at a series of known velocities to obtain a calibration slope, $L_{\mathrm{dyn}}$:

$$\frac{1}{2}\rho U_{\mathrm{probe}}^{2} \;=\; L_{\mathrm{dyn}}\overline{\Delta V}$$

***Figure 2: Photo of a Barnacle under test in the UoB water tunnel with an ADV for comparison***

Where $\rho$ is water density of 999 kg/m$^3$, $U_{\mathrm{probe}}$ is the velocity magnitude seen by the Barnacle probe (identical to water tunnel velocity in the calibration work) and $\overline{\Delta V}$ refers to the average difference in voltage for the 4 probe signals from their 'gauge-zero' values (that is the voltage in static water). Figure 3 shows the calibration data as a plot of dynamic head against mean voltage change $\overline{\Delta V}$. The blue circles show the data used to obtain the linear fit, which gives $L_{\mathrm{dyn}}$= 1388 Pa/V. The red squares show data taken on a different day, to check repeatability. It can be seen that the agreement is good, i.e. the calibration is consistent. The gauge zero level of the transducers is known to drift, especially with temperature. The consequence of this drift is that a 'gauge zero' reading must be taken in static water prior to each measurement campaign. In tidal flows, gauge zero values are automatically acquired twice a day at slack water.

As described above, the pressure on each face of the probe depends on the flow angle relative to the probe. Producing a calibration map which relates the left/right (yaw) and top/bottom (pitch) pressure differences to flow angles enables the velocity vector to be resolved in an unknown flow. The yaw and pitch coefficients of the probe are shown in Figure 4. Data is all taken from tests with a mean flow speed of 0.4 m/s. The red circles/squares show two sets of data taken with the probe at different yaw angles, and the blue line is a 4$^{\text{th}}$ order polynomial fit to the data. The probe performs as expected with increased pressure difference at increased flow angles. At high yaw angles, flow separation on one face causes the yaw coefficient to become large. This phenomenon is well-documented and limits the range of flow angles for which the probe can be used (adding more transducers and using machine learning are two methods for increasing the flow angle range, but usually the probe can be yawed to point in approximately the mean flow direction, see [6-10]).

Understanding the Barnacle performance with pitch is more complex, as the rotation of the probe causes a change in the hydrostatic pressure difference between ports. To correct for this, data was taken for the probe in still water at different pitch angles. The corrected data is shown as blue circles in Figure 4. It can be seen that this data follows a similar trend to the yaw data; this result gives confidence in the correction method.

**Low-speed flow accuracy**

The water tunnel has a convenient feature of a resonance with a period of about 8 seconds which lasts for 10-20 cycles after any abrupt change in the pump motor frequency. This made an excellent test for the resolution of turbulence from background noise in the region of ~0.1Hz. Figure 5 shows the flow speed measured by the two devices during a transient slowing from 0.3 m/s to 0.2 m/s. The Vector was returning correlation values in the range of 91-96, meaning that the data was of good quality. The Barnacle's calibration slope is taken from Figure 3 (i.e. a separate test), and a gauge zero was taken at the start and finish of this test. Both data sets have been filtered at 2 Hz to remove high-frequency noise (more of an issue for the Vector than the Barnacle).

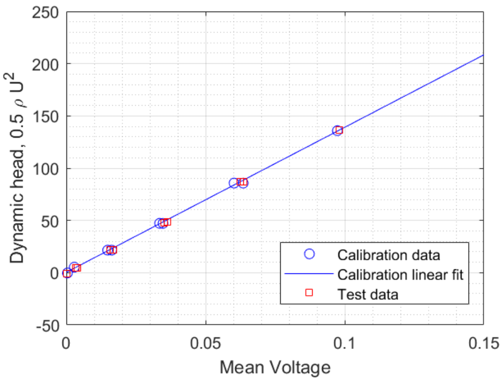


***Figure 3: Calibration data showing the linear relationship between mean voltage and dynamic head.***

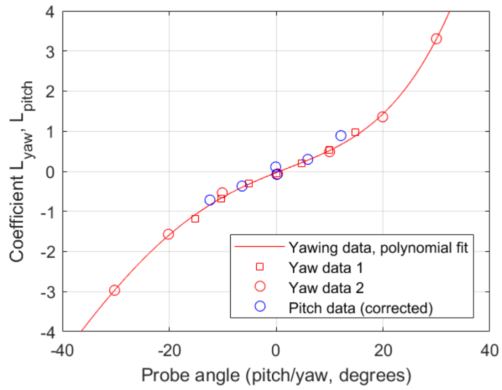


***Figure 4: Yaw and pitch calibration for the Barnacle probe in the water tunnel.***

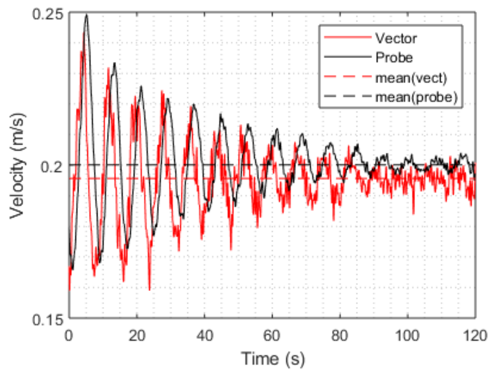


***Figure 5: Velocity against time for tunnel transient, flow speed stepping down to 0.2 m/s.***

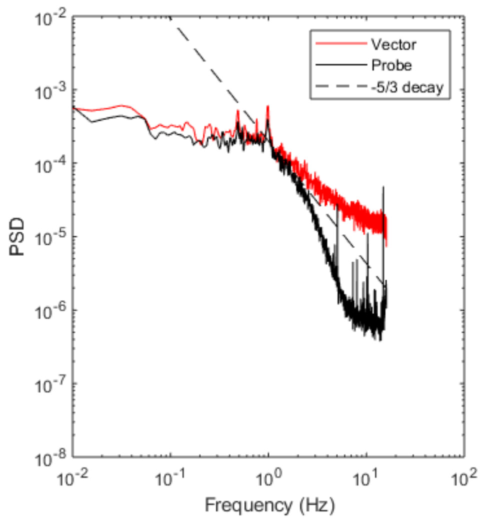


***Figure 6: Power spectral density for the Barncale probe and the Vector in the wake of a 75 mm diameter cylinder (mean flow speed 0.2 m/s).***

A 75 mm diameter cylinder was used to generate unsteady flow content in the water tunnel in a steady flow of 0.2m/s nominal. Frequency spectra obtained from the Barnacle and Vector are shown in Figure 6 (sampling at the same location but different times). Both devices register the peak at ~1 Hz, before diverging at ~2 Hz. The probe spectrum drops off more strongly than the theoretical -5/3 decay, while the vector data follows a shallower drop-off. The reason for the Barnacle diverging negatively from the slope of-5/3 is not certain. However, the axial separation between the centre and peripheral ports, of about 20mm, corresponds to a 0.1 second delay (a frequency of approximately 10Hz) for 0.2m/s, and we can expect decoherence between the ports for turbulent structures at and below this physical scale. Further, aliasing with the sampling rate (32Hz in this case), and the ~0.1 second delay might explain some of the high frequency spikes in the probe spectrum. Lastly, the Kolmogorov -5/3 spectrum is primarily a result applicable to fully developed turbulence and may not be a good approximation to the situation in a von Karman vortex street after only 10-20 diameters.

**Strangford Narrows**

Two Barnacles and two Vectors were deployed from the Minesto Barge in Strangford Narrows. The mounting arrangement is shown in Figures 6 and 7. The probes were deployed at approximately 0.5 m depth from the water surface and various data sets were acquired. Motion of the barge was minimal, and the support structure was stiffened to reduce resonance in the frequency range of interest. A short excerpt from one

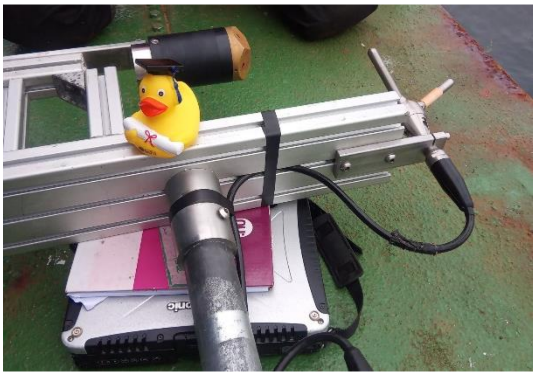

*Figure 7: Barnacle probe and Vector mounted for deployment (duck for scale).*

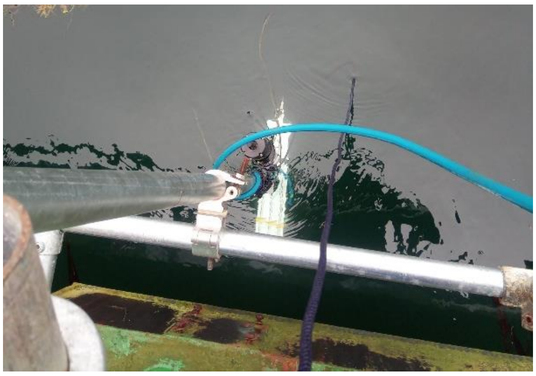

*Figure 8: Barnacle probe and vector mounted on the barge, deployed at 0.5 m depth.*

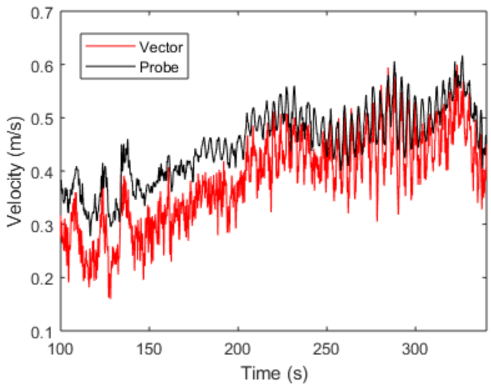


***Figure 9: Flow measured by Barnacle probe and Vector from Minesto barge in Strangford Narrows.***

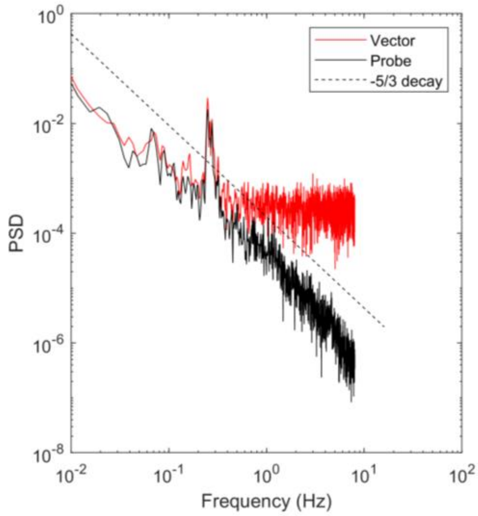


***Figure 10: Power spectral density of Barnacle and Vector data from Minesto barge.***

data set is shown in Figure 7 – data was acquired at 16 Hz and filtered at 2 Hz. It can be seen that the Barnacle and the Vector pick up the same fluctuations. The mean velocity is slightly different between the two devices (~15% difference). This is probably due to an error in the Barnacle probe's gauge zero.

The spectra (Figure 8) again show good agreement between the Barnacle and the Vector at low frequencies. The noise floor of the Vector is reached below 1 Hz, while the probe continues to show the expected -5/3 decay up to the Nyquist frequency (8 Hz). The spike at around 0.3 Hz in both spectra is due to wind-generated surface waves. These results show that the Barnacle performs as expected in the real marine environment and out-performs the Vector in terms of resolving higher frequencies.

**Conclusions and further work**

The Barnacle probe has been developed from a laboratory prototype to a robust marine device and has been shown to perform as well as an ADV in a tidal flow. This now opens up possibilities for low-cost turbulence measurements across a range of marine sectors. Follow-on funding has been secured from the University of Bath's EPSRC Impact Acceleration Account for exploring commercial opportunities for the Barnacle. The use of the probe in autonomous underwater vehicles is being explored with the National Oceanography Centre and the British Antarctic Survey (potentially via a NERC-GW4+ DTP studentship).

**References**

[1] R. U. Guion and A. M. Young, “The frequency response of acoustic Doppler current profilers: Spatiotemporal response and implications for tidal turbine site assessment,” in Proc. Oceans-St. John’s, 2014, pp. 1–10.

[2] I.A. Milne, A.H. Day, R.N. Sharma, R.G.J. Flay, The characterisation of the hydrodynamic loads on tidal turbines due to turbulence, Renewable and Sustainable Energy Reviews, Volume 56, 2016 851-864.

[3] P. Duquesne, C. Deschênes, M. Iliescu, and G. Ciocan, “Calibration in a potential water jet of a five-hole pressure probe with embedded sensors for unsteady flow measurement,” in Proc. 4th Int. Conf. Exp. Mech., 2009, pp. 752217–752217.

[4] P. Duquesne, G. D. Ciocan, V. Aeschlimann, A. Bombenger, and C. Deschênes, “Pressure probe with five embedded flush-mounted sensors: Unsteady pressure and velocity measurements in hydraulic turbine model,” Exp. Fluids, vol. 54, no. 1, p. 1425, 2013.

[5] A. M. Young, N. R. Atkins, C. J. Clark and G. Germain, "An Unsteady Pressure Probe for the Measurement of Flow Unsteadiness in Tidal Channels," IEEE Journal of Oceanic Engineering, vol. 45, Oct. 2020.

[6] M. J. Dunkley, “The aerodynamics of intermediate pressure turbines,” Ph.D. dissertation, Cambridge, U.K.: Univ. Cambridge, 1998.

[7] B. F.Hall and T. Povey, “The oxford probe: An open access five-hole probe for aerodynamic measurements,” Meas. Sci. Technol., vol. 28, Jan. 2017, Art. no. 035004.

[8] T. J. Dudzinski and L. N. Krause, “Flow-direction measurement with fixed-position probes,” NASA Tech. Memorandum X-1904, NASA Lewis Research Center, Cleveland, OH, USA, Tech. Rep. NASA-TM-X-1904, 1969.

[9] R. Dominy and H. Hodson, “An investigation of factors influencing the calibration of 5-hole probes for 3-d flow measurements,” ASME J. Turbomachinery, vol. 115, pp. 513–519, 1993.

[10] R. W. Ainsworth, J. L. Allen, and J. J. M. Batt, “The development of fast response aerodynamic probes for flow measurements in turbomachinery,” in Proc. ASME Int. Gas Turbine Aeroengine Congr. Expo., 1994, Paper V005T15A002.