NOVEL USAGE OF FIVE-HOLE PROBES: TIDAL CHANNEL TURBULENCE MEASUREMENTS

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ABSTRACT

A fast-response five-hole probe has been developed for the measurement of turbulent flow structures in tidal channels. Such measurements are vital for accurate prediction of unsteady loads on tidal turbines. Existing field-based velocimeters are unable to capture the required range of frequencies or are too expensive to profile the variation of turbulence across a typical tidal power site, and thus the data they provide is inadequate for turbine design.

This work adapts an established measurement technique from the turbomachinery community – a fast-response, multi-hole pneumatic probe – to achieve a low cost device which covers the required frequency range for tidal turbine applications. The main issues to be overcome in the marine environment are: the fact that, at depth, the ambient hydrostatic pressure is much higher than the dynamic pressure, and the need for devices to be water-tight and robust. These issues have been addressed by using novel calibration coefficients and by installing the sensors and amplifier board within the probe head.

A prototype device has been tested in a flume tank using LDV measurements for comparison. The probe can now be developed for trials in the marine environment.

NOMENCLATURE

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
c	Wave propagation speed
D	Denominator
f	Frequency
p	Static pressure
p_0	Stagnation pressure
p_L	Left-hole pressure
p_R	Right-hole pressure
p_C	Centre-hole pressure
p_U	Top-hole pressure
p_D	Bottom-hole pressure
K_{yaw}	Yaw calibration coefficient
K_{pitch}	Pitch calibration coefficient
K_{dyn}	Dynamic pressure calibration coefficient
K_{tot}	Total pressure calibration coefficient
LDV	Laser Doppler Velocimeter
$\bar{U}$	Bulk flow speed
CMRR	Common Mode Rejection Ratio

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 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 device can scan across the full depth of the channel while mounted on the seabed. However, it has been shown in previous work by Guion and Young [1] that a standard ADCP cannot capture fluctuations smaller than the radius of a typical turbine (10 m). By contrast, flow structures as small as half a blade chord (0.5 m) are likely to cause unsteady loading issues. The unresolved frequency content in ADCP data could lead to an under prediction of the unsteady loading and therefore there is the potential for unexpected mechanical failure.

Acoustic Doppler Velocimeters (ADVs) could be used in place of ADCPs as they can capture much smaller flow structures. However, they are less robust than ADCPs and take measurements at a single location, so 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 with lengthscales of the order of half a blade chord. Given the bulk convection speeds found in typical tidal channels, this translates to a minimum frequency response of approximately 10 Hz.

The use of multi-hole pneumatic probes is commonplace in conventional turbomachinery research. For applications where space constraints are not too onerous, fast-response versions have been developed with the sensing components built

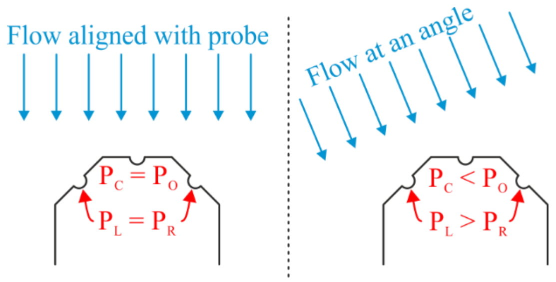


Figure 1: Principles of operation of a five-hole probe.

into the probe head. Most recently, a fast-response five-hole probe has been developed by Duquesne et al. [2, 3] and tested in small-scale, low hydrostatic head water pumps. The major difference between their work and the application discussed here is the background hydrostatic pressure, which is up to two orders of magnitude larger than the dynamic pressure in a typical tidal channel and thus dwarfs any changes in pressure due to unsteady flow passing over the sensors.

The prior art in the area of pneumatic probes therefore suggests that the technology could be transferred into the marine environment in order to provide unsteady flow measurements, if the high hydrostatic pressure can be accommodated without sacrificing accuracy.

This paper discusses the development of a prototype marine five-hole probe. It has been benchmarked against an LDV reference system which has been tested in the flume tank at Ifremer, Boulogne-sur-Mer, France. The flume tank has a working section which is 2 m deep by 4 m wide and a background turbulence level of approximately 5%. The tank is equipped with wave maker paddles for combined wave and current testing. The maximum flow speed is 1.6 m/s with clean flow and 0.8 m/s with waves. For further details of the test facility, see [4].

In the tests at Ifremer, the probe was shown to capture frequencies up to 30 Hz – more than sufficient for the calculation of unsteady loads on a tidal turbine.

This paper outlines aspects of the design of the probe, details the novel calibration coefficients and then finishes by presenting the benchmark comparison data.

MULTI-HOLE PNEUMATIC PROBES

Multi-hole probes are commonly used in aerospace applications to measure the velocity and static and stagnation pressures of flows. A section through the probe head is shown schematically in Fig. 1. The centre, left and right holes are shown. On the left-hand diagram, the probe is aligned with the flow; this means that the left and right holes will give equal pressure readings, and the centre hole will register the stagnation pressure of the hole. If the flow is at an angle to the probe, as shown on the right-hand diagram in Fig. 1, one of the side holes will read a higher pressure than the other, and the centre hole will no longer give the stagnation pressure.

By acquiring data with the probe at different yaw and pitch angles in a known, uniform flow, the calibration maps can be generated, which give the relationship between flow direction and the relative hole pressures. The most commonly-used calibration coefficients are:

$$K_{\text{yaw}} = \frac{p_{\text{L}} - p_{\text{R}}}{p_{\text{C}} - {}^{1}\!/_{4}\,(p_{\text{L}} + p_{\text{R}} + p_{\text{U}} + p_{\text{D}})}$$

$$K_{\text{pitch}} = \frac{p_{\text{U}} - p_{\text{D}}}{p_{\text{C}} - {}^{1}\!/_{4}\,(p_{\text{L}} + p_{\text{R}} + p_{\text{U}} + p_{\text{D}})}$$

$$K_{\text{dyn}} = \frac{p_0 - p}{p_{\text{C}} - {}^{1}\!/_{4}\,(p_{\text{L}} + p_{\text{R}} + p_{\text{U}} + p_{\text{D}})}$$

$$K_{\text{stag}} = \frac{p_0 - p_{\text{C}}}{p_{\text{C}} - {}^{1}\!/_{4}\,(p_{\text{L}} + p_{\text{R}} + p_{\text{U}} + p_{\text{D}})}$$

The calibration maps derived from a known flow can then be applied to data acquired in a wind tunnel test or aero-engine environment and the flow speed and direction derived along with the stagnation and static pressures.

At high yaw/pitch angles, the flow on one of the faces of the probe will separate, this causes a sharp drop in pressure on one face. The behaviour of the probe when the flow is separated can be highly dependent on Reynolds' number, so researchers usually aim to use their probes only within the un-separated range, and it is preferable 'null' the probe such that the side face pressures are equalised before measurements are taken, instead of relying on the accuracy of the extreme edges of the calibration map. This approach cannot, however, be taken in an unsteady flow environment, and so various adjustments to the calibration coefficients can be made to increase the accuracy of data at high angles. This is discussed in the Test Results section.

SIZE AND SCALE CONSIDERATIONS

The typical range of conditions in a tidal channel are compared to those encountered in aerospace applications in Table 1. It can be seen that the increase in density between air and seawater is offset by much lower flow speeds in the sea, such that the dynamic pressures expected in a tidal channel are comparable to the low speed end of typical aerospace test facilities. This, along with the blade Reynolds' numbers being in the same range, suggests that similar measurement techniques will be appropriate for both flows. However, there are some major differences between the two applications: hydrostatic pressure, unsteady flow lengthscales, probe Reynolds' number and compressibility. The main differences in

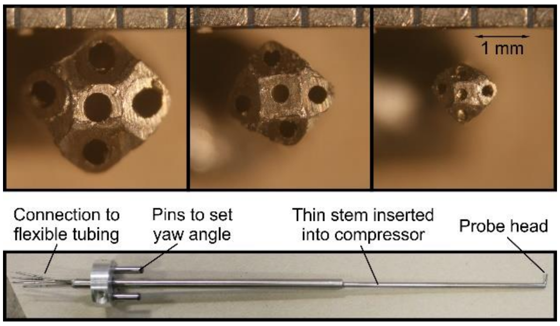


Figure 2: Miniature five-hole probe for aero-engine applications (figure reproduced with permission from Grimshaw and Taylor [5]).

measurement requirements between aero-engines and marine channels will now be discussed in turn.

Pressures

The hydrostatic pressure at 20 m depth (the hub height of a typical 1 MW turbine) will be almost 200 kPa, which is between 45 and 400 times larger than the dynamic head. In order to measure the flow speed accurately, the dynamic pressure measurement must therefore be isolated from the hydrostatic pressure. Differential pressure transducers with full-scale range similar to the dynamic head are thus essential in this application. The exclusive use of differential transducers necessitates a novel set of calibration coefficients, which will be discussed in detail below.

Unsteady Flow Lengthscales

In an aero-engine, researchers are usually interested in high-frequency, small-scale flow features related to loss generation. In a tidal turbine, however, the major need is to capture the unsteady flow structures in the channel. This means that the scales of interest are vastly different in the two applications, as shown in Table 1.

To give an idea of the scale of aero-engine probes, a series of miniature five-hole probes manufactured by Grimshaw and Taylor [5] are shown in Fig. 2. It can be seen that they are of order 1 mm in diameter. The minimum scale of interest in an aero-engine is typically set by wake thickness, and the ratio of probe diameter to trailing edge thickness is of order 1.

As explained above, a tidal turbine designer will only need information on unsteady flow structures down to scales equivalent to half the turbine chord in order to predict unsteady loading. The 75 mm diameter probe discussed here, when compared to a typical chord of 1 m, is a factor of six smaller than the flow features of interest.

The lengthscale difference also has implications for frequency range. The frequencies of interest in an aero-engine will be multiples of the blade passing frequency (tens or hundreds of kHz). As explained above, the frequency required for tidal channel

	Quantity	Tidal	Aero (sea level)
Working fluid	Density (kg/m^3)	997	1.225
	Kinematic viscosity (m^2/s)	1.0×10^{-6}	1.6×10^{-5}
	Flow speed (m/s)	1 – 3	30 – 300
Reynolds' numbers	Typical blade chord (m)	1	0.05
	Typical blade Reynolds' number	$1 – 3\times10^6$	$0.1 – 1\times10^6$
	Typical probe diameter (mm)	75	1 – 10
	Typical probe Reynolds' number	$75 – 230\times10^3$	$2 – 100\times10^3$
Pressures	Depth (m)	10 – 80	n/a
	Hydrostatic pressure (gauge, kPa)	99 – 790	n/a
	Dynamic pressure ($p_0 - p$, kPa)	0.49 – 4.5	0.55 – 55
Lengthscales	Flow lengthscales of interest	0.5 – 35 m	1 – 50 mm
	Max. frequency of interest (Hz)	10	50 000
	Kolmogorov microscale (μm)	50 – 100	1 – 8

Table 1: Comparison of flow properties for tidal and aero applications.

measurements is far lower, at 10 Hz. This therefore allows the use of lower cost components.

The larger size also gives more space for mounting transducers in the probe head, and makes it more straightforward to build a robust, water-tight device.

The turbulence intensity in a tidal channel flow can reach 20%, and so it is worth noting at this point that Dominy and Hodson [7] found that the turbulence intensities of up to 10% had a very limited effect on probe performance. This means that a five-hole probe calibrated in clean flow should give reliable data even in highly turbulent tidal channel flow.

Probe Reynolds' number

The Reynolds' number of the probe developed in this work (75 mm diameter) is compared to that of typical aerospace probes in Table 1. It can be seen that there is an overlap in the range of Reynolds' numbers experienced in the two applications. Work by Dudzinski and Krause [6] on fixed orientation probes[1], and their sensitivity to Reynolds' number, showed that in some circumstances the probe must

[1] As opposed to probes which are 'nulled' to face the bulk flow.

be calibrated at a series of different Reynolds' numbers in order to obtain accurate data.

Building on this work, Dominy and Hodson [7] undertook a series of tests with different probes and flow speeds. They found that the calibration map was approximately independent of Reynolds' number as long as the above 15×10^3, which is 5 times less than the Reynolds' number of the prototype probe discussed here. Their work therefore means that the prototype probe developed here should give readings that are independent of Reynolds' number.

Compressibility

It is clear that the flow in a tidal channel will be incompressible, and therefore the complications arising from compressibility can be safely ignored.

NEW CALIBRATION COEFFICIENTS

In order to overcome the issue of high ambient hydrostatic pressure, differential transducers must be used, and this in turn requires a novel set of calibration coefficients. Each transducer measures the difference in pressure between the centre hole and one of the four side holes. In this way, yaw and pitch coefficients can be calculated as with a conventional probe, and the dynamic pressure can be found.

It can be seen that the conventional yaw coefficient:

$$K_{\mathrm{yaw}} = \frac{p_{\mathrm{L}} - p_{\mathrm{R}}}{p_{\mathrm{C}} - {}^{1}/_{4}\,(p_{\mathrm{L}} + p_{\mathrm{R}} + p_{\mathrm{U}} + p_{\mathrm{D}})}$$

can be obtained using differential signals via the following mathematically equivalent expression:

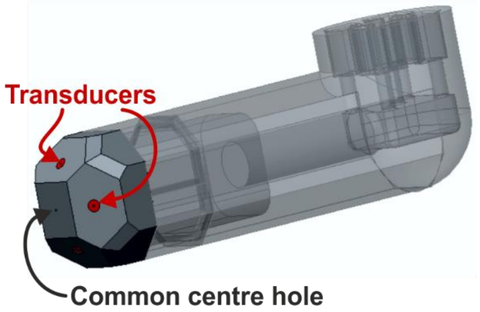
$$K_{\mathrm{yaw}} = \frac{(p_{\mathrm{C}} - p_{\mathrm{R}}) - (p_{\mathrm{C}} - p_{\mathrm{L}})}{{}^{1}/_{4}\begin{bmatrix}(p_{\mathrm{C}} - p_{\mathrm{L}}) + (p_{\mathrm{C}} - p_{\mathrm{R}}) + (p_{\mathrm{C}} - p_{\mathrm{U}}) \\ +(p_{\mathrm{C}} - p_{\mathrm{D}})\end{bmatrix}}$$

Similar expressions for the pitch coefficient, K_{pitch}, and the dynamic coefficient, K_{dyn}, can also be found:

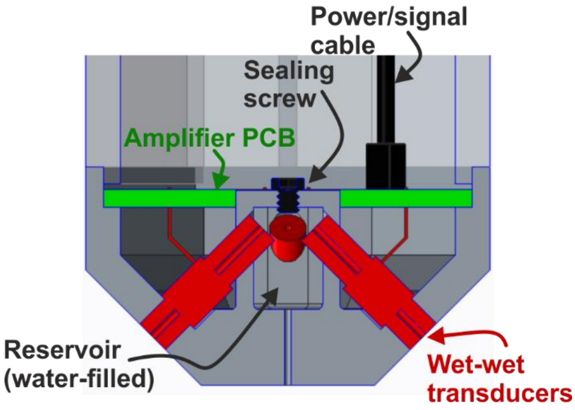
$$K_{\mathrm{pitch}} = \frac{(p_{\mathrm{C}} - p_{\mathrm{D}}) - (p_{\mathrm{C}} - p_{\mathrm{U}})}{{}^{1}/_{4}\begin{bmatrix}(p_{\mathrm{C}} - p_{\mathrm{L}}) + (p_{\mathrm{C}} - p_{\mathrm{R}}) + (p_{\mathrm{C}} - p_{\mathrm{U}}) \\ +(p_{\mathrm{C}} - p_{\mathrm{D}})\end{bmatrix}}$$

$$K_{\mathrm{dyn}} = \frac{p_0 - p}{{}^{1}/_{4}\begin{bmatrix}(p_{\mathrm{C}} - p_{\mathrm{L}}) + (p_{\mathrm{C}} - p_{\mathrm{R}}) + (p_{\mathrm{C}} - p_{\mathrm{U}}) \\ +(p_{\mathrm{C}} - p_{\mathrm{D}})\end{bmatrix}}$$

From the dynamic pressure coefficient, the flow speed can be derived via Bernoulli's equation (as the flow is incompressible). The total pressure coefficient, however, cannot be derived from the differential measurements available. This means that the absolute static and stagnation pressures



(a) General view.



(b) Section view.

Figure 3: Drawing of probe head design and transducer location.

cannot be found (unless an additional, absolute transducer
is fitted). This is not of concern in the current work, as the quantities of interest are flow speed and direction, for which the yaw, pitch and dynamic coefficients are sufficient.

PROTOTYPE PROBE

The prototype probe is shown schematically in Fig. 3(a). The probe diameter is 75 mm, and the distance from the front of the probe to the right-angle in the stem is approximately three diameters. The prototype was built using low-cost off-the-shelf components.

While a marine probe does not have to withstand the high temperatures encountered in some parts of an aero-engine, it does have to survive in a corrosive fluid (sea water) at high pressure. The probe in Fig. 3 was made from 4 parts which were 3D printed using a polymer with similar properties to ABS or polypropylene (depending on the life-span required, production models could be machined from marine-grade stainless steel).

It can also be seen from Fig. 3(a) that the prototype has a conventional five-hole probe head, with two design features suggested by Dominy and Hodson [7]. Firstly, the faces are at 45° to one another with sharp edges. This design gives superior performance to a cone-type probe at high yaw and pitch angles. Secondly, the holes are perpendicular to, and at the centre of, each face – moving the holes back from the front edge reduces the effect of Reynolds' number on the probe calibration map. Ainsworth et al. [8] found that the optimal hole position is not necessarily at the centre of the face. However, the holes are central on the prototype for reasons of ease of construction.

An internal section view of the probe is given in Fig. 3(b). It can be seen that the device has on-board amplification and there is sufficient space within the body for on-board data acquisition and a battery, as is common in marine measurement devices. (Remote operation and data storage are both vital for marine deployment where the distance to the surface is too large to allow for operation from a PC.)

The electronic components are protected from exposure to water, with the exception of the transducers, which are wet-wet and are exposed to water on both sides of their diaphragms.

The pressure sensors used are low-cost commercial-off-the-shelf wet-wet differential transducers with a full scale range of 7 kPa (to the author's knowledge, this was lowest range wet-wet part available with sufficiently small dimensions). Although 7 kPa is appropriate for a typical tidal channel flow, the flume tests were run at 0.8 m/s, which is the very low end of expected field conditions. As such, the peak dynamic head in the flume is only about 0.5 kPa. In addition, the transducers have a full scale output of 16.7 mV, which is relatively low. In order to generate usable data from such small signals, a low noise, high CMRR instrumentation amplifier was fitted within the probe head. The amplifier had a differential gain of 200, and a line driver was incorporated into a custom PCB which was fitted immediately behind the transducers.

The transducers are mounted directly in the holes on the faces, with the minimum possible tube length. The four rear ports of the transducers are immersed in a reservoir which is connected to the centre hole of the probe. This means that each transducer will measure the difference between the centre hole and one of the side holes, thus eliminating the hydrostatic pressure as described above.

As water is incompressible, the effect of having a reservoir on the frequency response of the probe should be negligible. However, the presence of an air bubble anywhere between the probe faces and the transducer diaphragms is likely to introduce a resonant response. In order to prevent this, the centre hole was sealed temporarily, and the probe orientated with the centre hole facing downwards. Whilst in this configuration, the reservoir and the transducer ports were filled with water using a syringe. This process was repeated over a period of several hours to allow air bubbles to rise to the surface.

Once the reservoir was full and free of air bubbles, the sealing screw was inserted and the

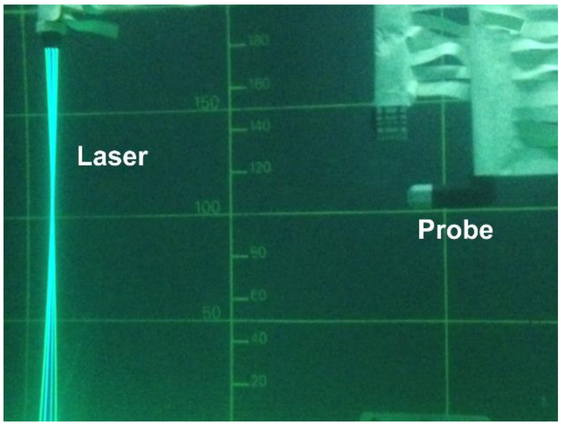


Figure 4: Test setup in flume tank at Ifremer with LDV upstream of prototype probe.

centre hole was re-opened at the same time to prevent overpressure. The front ports of the transducers were also filled with water in a similar manner. Care was taken to keep the reservoir and ports full during transit.

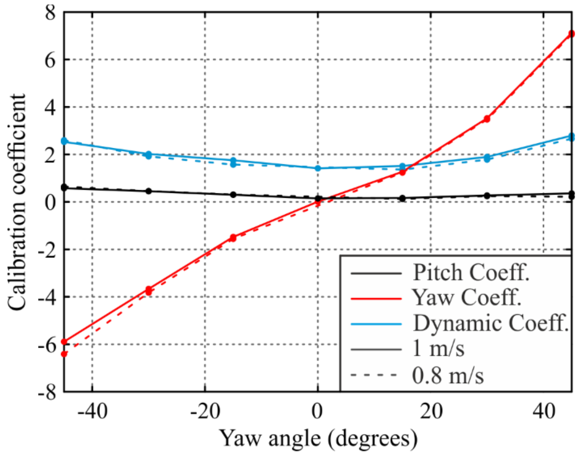
The scale of the probe means that it would be relatively straightforward to implement an analog to digital conversion and storage system in the head. For the purpose of this test, however, a standard laboratory grade data acquisition system was used, connected by ~3 m cables, immediately above the water surface and controlled by a desktop PC.

TEST RESULTS

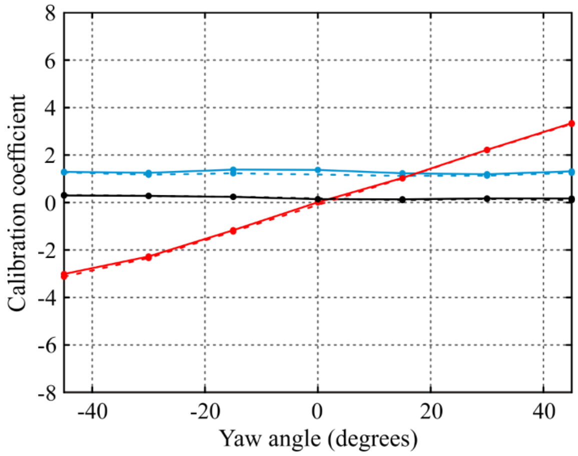
The probe was fitted centrally at mid-depth in the flume at Ifremer and tested in flow speeds of 0.8 and 1.0 m/s in clean flow, and at 0.8 m/s with 0.5 Hz surface waves (100 mm wave height). In all tests, a Laser Doppler Velocimeter (LDV) was set up 2.5 m upstream of the probe and data acquisition was undertaken simultaneously so as to provide reference measurements. A photo of the test setup is shown in Fig. 4.

The probe-holder was designed such that the probe head could be yawed, but the pitch angle could not be adjusted. This allowed a yaw calibration to be undertaken. The pitch calibration should be almost the same due to the symmetry of the probe, but some small variation may be present due to stem effects. (Manufacturing errors are negligible on a probe of this size.)

The calibration coefficients are shown in Fig. 5(a) as a function of yaw angle for tests with flow speeds of 0.8 m/s and 1 m/s. It can be seen that the probe behaves as expected: the dynamic pressure coefficient is approximately constant for angles less than ±20º, while the yaw coefficient is linear over the same range. At larger yaw angles, separation on whichever face is at the most extreme angle to the flow causes the coefficients to deviate. Encouragingly, there is very little variation between the curves for the two flow speeds, suggesting that Reynolds' number effects are minimal (at least over the speed range tested here).



(a) Using all four holes.



(b) Neglecting hole with lowest pressure.

Figure 5: Calibration coefficients against yaw angle for two flow speeds.

The best way to minimise errors due to Reynolds' sensitivity and data uncertainty is to avoid using the probe at high angles of attack where one face is separated. This is usually achieved by 'nulling' the probe such that it faces the bulk flow direction.

In situations where this is not possible, due to high levels of unsteadiness, or the probe being fixed (both of which will be true in a tidal channel), the angle range of the probe can be improved by changing the denominator of the calibration coefficients. There are numerous permutations in the literature, including those of Dunkley [9], who used a weighting factor to bias the denominator towards the holes which were closest to the local stagnation pressure. For the prototype probe with the differential measurements discussed here, it was found that neglecting the lowest pressure reading in each data set improved the angle range. Using this method, the denominator becomes:

$$D = p_\mathrm{C} - \frac{1}{3}\Big\{p_\mathrm{L} + p_\mathrm{R} + p_\mathrm{U} + p_\mathrm{D} - \min_{\mathrm{L,R,U,D}}[p_\mathrm{L}, p_\mathrm{R}, p_\mathrm{U}, p_\mathrm{D}]\Big\}$$

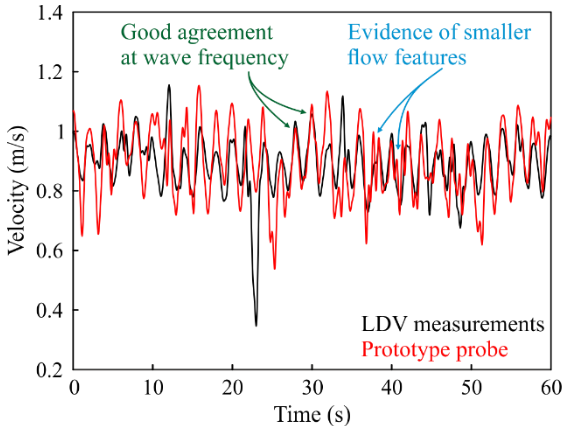


Figure 6: Comparison of raw signals from LDV and prototype probe (0.8 m/s average flow speed, with waves at 0.5 Hz).

This change prevents the denominator from becoming very small at high angles, when the flow has separated on one face, and thus produces a more linear dependence of yaw coefficient on flow angle, as shown in Fig. 5(b). It can also be seen that the dynamic pressure coefficient is more constant across the range of angles tested when the minimum pressure is neglected in this way.

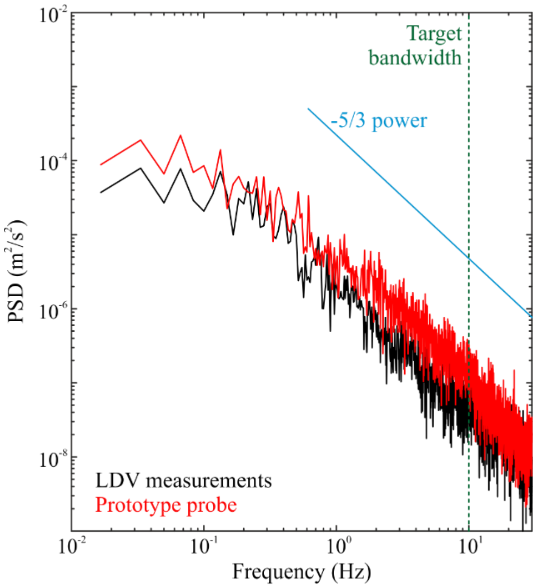
If extreme values of pitch and yaw were expected to occur simultaneously, the denominator could be further refined to neglect the lowest two pressures, or a more sophisticated algorithm could be used for deciding how many pressures to neglect.

The spatial offset (2.5 m) between the LDV and the probe means that it is necessary to shift the signals in time in order to compare unsteady velocity measurements. However, different flow structures will convect at different speeds. The two primary speeds at which structures may convect are the bulk flow speed, $\overline{U}$, and the speed of the surface waves, which is given by:

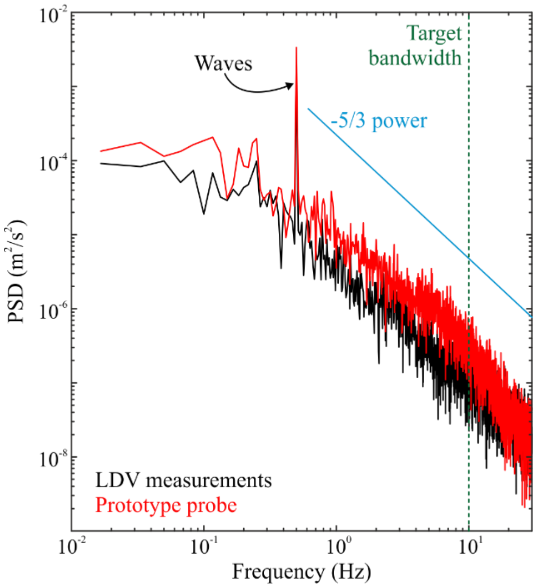
$$c = \overline{U} + \frac{g}{2\pi f}$$

where f is the frequency of the waves. The propagation speeds of other structures are unknown, and new small structures are likely to evolve between the two measuring locations.

A comparison of the flow velocity between the two devices is given in Fig. 6, with a temporal shift to account for the spatial offset between probes. The data shown is from a test at 0.8 m/s with waves at 0.5 Hz; both measurements have been filtered to remove all content above 2 Hz. It can be seen that both the LDV (black line) and the probe (red line) capture the waves, and they agree on the longer time-scales of unsteadiness in the tank. The higher frequencies indicate the presence of smaller turbulent flow structures, which will not be constant between the two locations. However, in periods when higher frequencies are absent, the agreement is good.



(a) No waves.



(b) With waves (0.5 Hz).

Figure 7: Comparison of power spectral density from five-hole probe with LDV measurements with and without waves (0.8 m/s).

Although it is not reasonable to expect that individual gusts are frozen as they convect from the LDV measurement location to the probe, the flow is likely to be statistically homogeneous between the two points. Thus, a more instructive way of comparing the data is through the power spectral densities of the signals, as shown in Fig. 7.

From Fig. 7, it can be seen that there is good agreement between devices and the probe is able to resolve the 0.5 Hz waves clearly (Fig. 7(b)). The spectra agree well up to 30 Hz, at which point the signal from the probe reaches its noise floor. A frequency of 30 Hz corresponds to a 7 cm gust convecting with the flow – i.e. far smaller than the gusts that are important for tidal turbine design. This result, together with the low cost of the device, means that five-hole probes could be used to obtain high fidelity turbulence measurements at tidal power sites and thus give a vast improvement in unsteady load prediction.

FUTURE IMPROVEMENTS

The tests with the prototype device have shown that a five-hole probe can be used to capture unsteady flow features in a tidal channel flow. There are, however, some further improvements which need to be made in a production-ready device.

The first change is to integrate the data acquisition and power so that the probe operates remotely without a cable connecting to the surface. This would be achieved by placing a second PCB and a battery in the probe head, such that the device could be switched on and deployed to acquire data for a set period of time. The probe would then be retrieved and data transferred via an IP-68 rated Ethernet port. This connection would also allow monitoring and control in a laboratory environment.

Secondly, a fifth transducer which measures the absolute hydrostatic pressure (to give depth readings) and a gyroscope to give the orientation of the probe would enable the precise position and direction of the probe to be measured while flow data was acquired. Again, there is space in the probe head for an additional PCB to house these devices.

CONCLUSIONS

It has been shown that the unsteady five-hole probe represents a viable, low-cost means of obtaining turbulence measurements in tidal channels. The data provided by such a probe is of huge importance for tidal stream turbine development, where high-fidelity information on the inflow conditions across the whole site is needed in order for accurate fatigue life assessments to be made.

The primary difference between traditional five-hole probes used in air and the new marine probe demonstrated here is the use of differential rather than absolute pressure measurements. The transducers are installed such that each measures the difference in pressure between one of the four side faces and the central hole. This, along with novel calibration coefficients, allows the dynamic pressure to be measured accurately despite its small magnitude relative to the hydrostatic pressure.

A prototype probe has been built using off-the-shelf electronic components, with a bespoke amplifier for space reasons. In tests at a water channel facility, the probe was shown to give accurate flow information at 0.8 m/s and 1 m/s at 1 m depth. In tests alongside an LDV system, unsteady flow features, including waves, were captured accurately by the probe at frequencies of up to 30 Hz. This is well in excess of the frequencies required for tidal turbine fatigue life design calculations.

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