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Article

Experimental Assessment of Flow, Performance, and Loads for Tidal Turbines in a Closely-Spaced Array

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Abstract: Tidal stream turbines are subject to complex flow conditions, particularly when installed in staggered array configurations where the downstream turbines are affected by the wake and/or bypass flow of upstream turbines. This work presents, for the first time, methods for and results from the physical testing of three 1/15 scale instrumented turbines configured in a closely-spaced staggered array, and demonstrates experimentally that increased power extraction can be achieved through reduced array separation. A comprehensive set of flow measurements was taken during several weeks testing in the FloWave Ocean Energy Research Facility, with different configurations of turbines installed in the tank in a current of 0.8 m/s, to understand the effect that the front turbines have on flow through the array and on the inflow to the centrally placed rearmost turbine. Loads on the turbine structure, rotor, and blade roots were measured along with the rotational speed of the rotor to assess concurrently in real time the effects of flow and array geometry on structural loading and performance. Operating in this closely-spaced array was found to improve the power delivered by the rear turbine by 5.7%–10.4% with a corresponding increase in the thrust loading on the rotor of 4.8%–7.3% around the peak power operating point. The experimental methods developed and results arising from this work will also be useful for further scale-testing elsewhere, validating numerical models, and for understanding the performance and loading of full-scale tidal stream turbines in arrays.

Keywords: Tank testing; Tidal stream turbine; Array effects; Turbine wake measurements

1. Introduction

Full-scale tidal current turbines have now been installed in small arrays, generating and exporting electricity to the local network for several years, both with individual unit capacity up to 1.5 MW [1], and smaller 100 kW units operated in an array in Shetland since 2016 [2]. [These are demonstrating full scale devices at pre-commercial status, corresponding to a technology readiness level of 6–7.](#) The UK Crown Estate has granted seabed leases for 30 tidal current developments which, for commercial scale, will be deployed in arrays. For efficient use of the seabed the arrays may be closely spaced. For commercial operation this will require arrays of multiple devices. It is therefore important to understand the hydrodynamic (and potential electro-dynamic) interaction between these turbines, including the potential to increase the overall power generated by a carefully optimised layout of the array. Tank testing of instrumented scaled models provides the opportunity to explore these physical effects in a relatively low-cost, repeatable, controlled laboratory environment, which can be used to compliment and validate computer numerical modelling of potential array concepts.

This paper presents the methods employed and results from a significant experimental campaign that shows how the flow conditions in the FloWave current and wave test tank (EP/I02932X/1) are modified by the presence of and energy extracted by an array of three 1.2 m rotor diameter 1/15 scale model tidal turbines. These turbines were made and tested at the University of Edinburgh, as part of work of the EPSRC-sponsored SuperGen UK Centre for Marine Energy Research (EP/I027912/1), each identical with a 3-bladed horizontal axis turbine and four-quadrant controlled power take-off. The diameter-based Reynolds Number, Eq. (1), for all tests was 1.08×10^6 , where ρ is the density and μ the kinematic viscosity of water.

$$Re_D = \frac{\rho \bar{U} D}{\mu} \quad (1)$$

The flow measurements were made at over 150 spatial locations for four array installation configurations: with one, two, or three turbines installed, plus baseline empty tank measurements. This paper also reports the results of the investigation of how power developed and loading on the rear turbine were influenced both by the presence and defined operation of the front row turbines.

The results presented in this work arise from some of the largest laboratory-scale array tests of tidal current turbines undertaken or published to date. Testing at this large scale is necessary to reduce scale effects and to provide more representative understanding of full-scale turbine performance and loading in the sea.

The remainder of the paper is laid out as follows: Sections 1.1 and 1.2 summarise other relevant work on testing arrays of turbines, Section 2 describes the experimental set-up, methods, and analysis methods. The results obtained are covered in Sections 3 and 4, considering first the influence of the turbine array on flow velocities, and then how this affects loading and power. Section 5 discusses the relevance and implications of these findings, followed by the conclusions that may be drawn in Section 6.

1.1. Previous studies of tidal stream turbine arrays

The commercial deployment of tidal energy farms that is underway requires the deployment of arrays of multiple tidal current turbines in close proximity to one another, mandating an improved understanding of the interaction between individual turbines. A review of issues encountered when designing large arrays of tidal turbines was conducted by Vennell *et al.* [3], including a summary of key numerical modelling studies.

Due to the complex nature of turbulent flow around the machines in an array of rotating turbines, scale model testing is important to explore the physical processes, understand the modifications to the flow field, measure and characterise turbine performance and loading – with the resulting data and knowledge essential to validate numerical models.

Some previous tank tests of tidal turbine arrays have used static porous actuator disks to represent the energy extraction by the turbines [4–6]. In other tests, arrays of relatively small turbines (typically less than 0.4 m in diameter) have been used [7–10], with [9,10] considering cross-flow turbines and where the water depth was not scaled. A configuration with two 0.7 m diameter turbines, one directly in the wake of the other, has been tested in a flume [11,12]. Subsequently, Gaurier *et al.* [13] tested three of these turbines in a staggered array similar to the one presented in this work, but with 2D separation between the front turbines and the rear located 4D downstream. It is noted that in [7,8,11–13] the turbines were tested suspended from above the free surface, rather than bed-mounted, and only the thrust on the whole turbine and support structure was measured. Recently, two 1.2 m diameter turbines were tested at FloWave in a side-by-side configuration to assess the potential for constructive interference effects between them, which showed an increase in both power and thrust [14].

Apart from the above, the authors are not aware of other published studies of arrays of multiple large-scale turbines ($\gtrsim 1$ m diameter), highlighting the novelty of this work. Indeed the lack of data showing multi-turbine wake interactions was stated in [7]. As mentioned, the only other large

78 three-turbine array tests were presented in [13], where the downstream separation was $4D$ and the
 79 blockage induced by the two upstream turbines was 9.6%. They show detailed velocity measurements
 80 and turbine performance for two turbulence intensities and different lateral offsets of the rear turbine.
 81 In this current work, we explore a single array configuration with a downstream separation of just $1D$;
 82 exploring the implications of a highly compact array configuration. The blockage introduced by the
 83 upstream turbines is 4.5%, noting that blockage corrections are considered necessary above 5% [15].

84 1.2. Other studies using the Supergen UKCMER Tidal Turbines

85 The method and results of the experimental study presented here are from measurements made
 86 on a fully instrumented turbine installed as part of an array and subjected to realistic flow conditions
 87 in the FloWave combined current and wave test tank. Previous studies have demonstrated the design
 88 and results obtained from this turbine operating singly, not as part of an array [16–18]. Other results
 89 from this experimental campaign, exploring and reporting the influence of wave loading on a single
 90 turbine, are presented in [19–21].

91 2. Experimental set-up and methods

92 2.1. The FloWave Ocean Energy Research Facility

93 All the experimental work discussed in this paper was carried out at the FloWave Ocean Energy
 94 Research facility at the University of Edinburgh [22]. FloWave comprises a 25 m diameter circular tank,
 95 with an operating water depth of 2 m. In the centre is a 15 m diameter buoyant floor, that can be raised
 96 out of the water for model installation. A movable gantry spans across the tank, used to provide access
 97 to the floor and for mounting instrumentation.

98 As shown in Fig. 1, currents are generated by 28 impeller units mounted in the plenum chamber
 99 below the test floor. The flow is directed across the test volume of the tank by turning vanes mounted
 100 around the outside of the floor, below and in front of the wavemakers. Full details of the flow
 101 generation are given in Robinson *et al.* [23,24].

102 Due to the method of generating flow in a circular tank, there is some spatial variation of the
 103 mean flow across the test area. Characterisation by Noble *et al.* [25] shows there is a $\sim 50 \text{ m}^2$ region
 104 of relatively straight uniform flow ($\pm 10\%$) in the tank centre. Baseline turbulence characterisation of the
 105 tank's test area was conducted by Sutherland *et al.* [26]. Turbulence intensity I_U at 0.8 m/s is 5–10%
 106 and integral lengthscale ℓ_U is typically in the range 0.1 m to 0.5 m. At the primary turbine location
 107 these values are approximately 8% and 0.3 m.

108 The flow in the tank was set at the design flow speed of the turbine model [17], nominally 0.8 m/s
 109 inflow at a hub-height location without the turbine installed in the tank, which is consistent with
 110 previous tests with a single turbine [18]. This corresponds to a full-scale flow speed of 3.1 m/s.

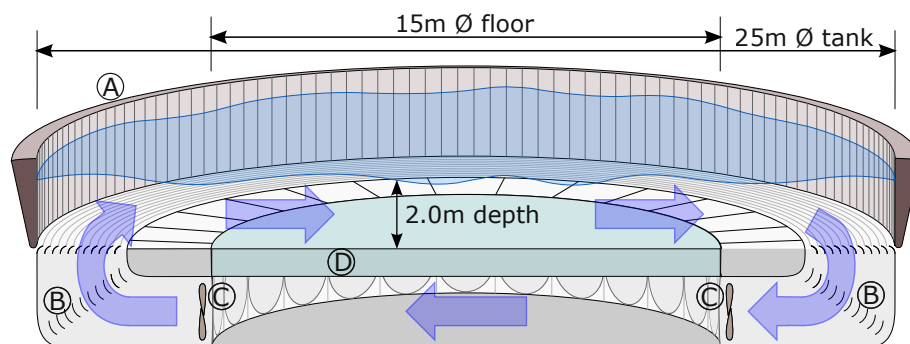


Figure 1. Sectional schematic of FloWave basin showing: (A) Wavemaker paddles around circumference; (B) Turning vanes and flow conditioning filters; (C) Current drive impeller units; (D) Buoyant raisable floor (15 m \varnothing) below test area. [25]

Table 1. Key turbine dimension (from [17])

Rotor diameter (mm)		1200	(1D)
Nacelle length (mm)		1030	
Nacelle diameter (mm)	hub to tower	120	
	beyond tower	160	
Hub height (mm)		1000	(0.83D)
Tower diameter (mm)		102	
Distance from rotor plane to tower axis (mm)		486	(0.4D)

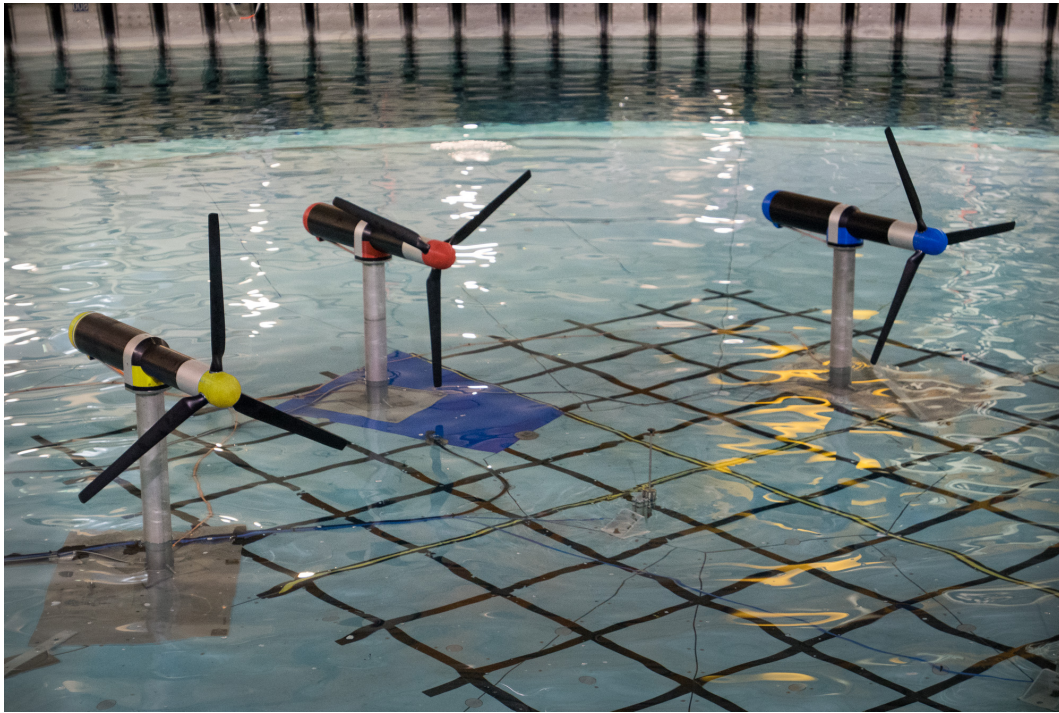


Figure 2. Turbine array installed in FloWave, as the floor descends after installation. Fully instrumented primary turbine (red fairing) in the centre between front turbines (yellow & blue). Array layout and configurations tested shown in Fig. 3. Grid on tank floor relative to tank centre, with 0.5 m spacing.

111 2.2. Turbines and instrumentation

112 An array of three similar turbines was used in these tests, one fully instrumented primary turbine
 113 with two additional turbines upstream to alter the inflow conditions as would happen in an array.

114 The turbines are a generic bed-mounted horizontal-axis three-bladed design, representative of
 115 many turbines proposed, modelled, or installed to date [e.g. 1,27]. The turbine models are nominally
 116 1:15 scale, corresponding to an 18 m diameter prototype. The design and manufacture of one of
 117 the model turbines used for these tests, including on-board instrumentation, is fully described in
 118 Payne *et al.* [17]. The blades have been designed to provide a rotor thrust coefficient similar to a
 119 full-scale generic turbine across a range of turbine rotational speeds. A summary of key turbine
 120 dimensions is provided in Table 1. To simulate the power take-off, a brushless servo motor is connected
 121 in a direct-drive set-up, i.e. without gearbox. **The servo motor was operated in speed control and**
 122 **was controlled using an ABB MotiFlex e180 servo drive [28].** Torque and thrust on the whole rotor is
 123 measured via a transducer connected to the hub, with absolute angular position of the blades measured
 124 through an encoder on the motor shaft. For the primary turbine only, streamwise root bending moment
 125 (RBM) sensors are also fitted to each blade. The Turbine instrumentation was logged at 256 Hz. **Note**
 126 **that all the measurements reported in this paper were made upstream of the servo drive.**

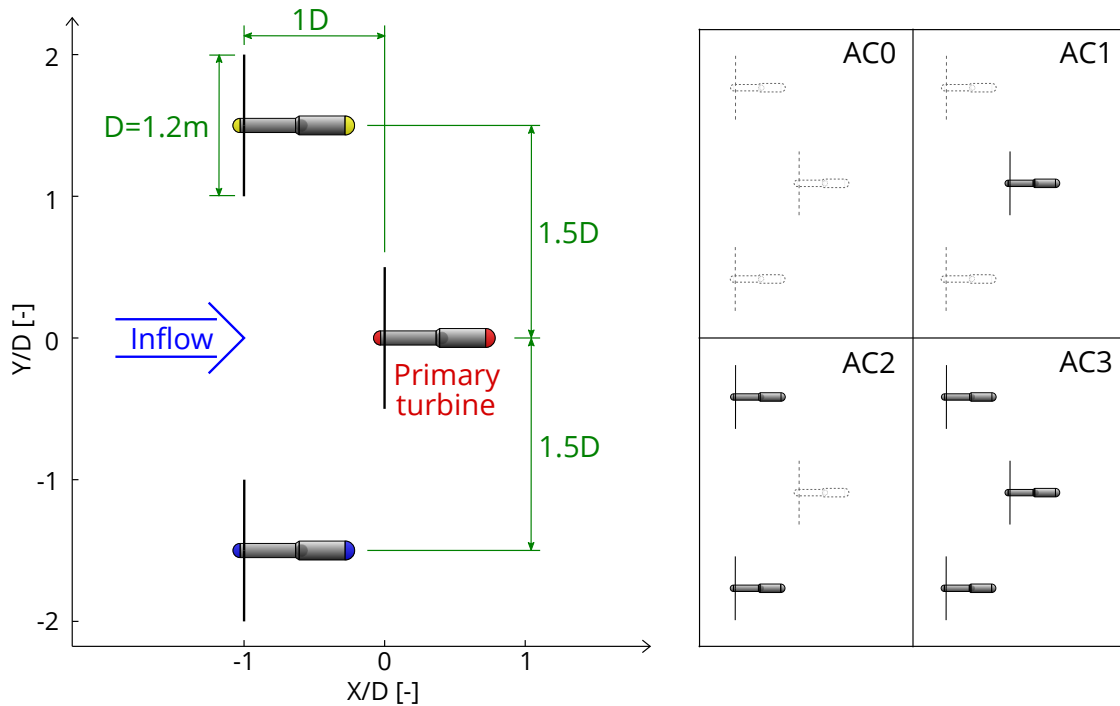


Figure 3. (left) three turbine array layout, and (right) four configurations tested: AC0 empty tank, AC1 primary turbine only, AC2 upstream turbines only, and AC3 full array.

127 The fully instrumented primary turbine (red fairing in Fig. 2) was mounted on a six degree
 128 of freedom load-cell to measure forces and moments on the foundation (although not used in this
 129 analysis). This load-cell is flush mounted within the tank floor, which dictates the location of this
 130 turbine, with the tower offset ~ 1.6 m downstream and ~ 0.5 m to the side of the tank centre.

131 2.3. Array configurations

132 To investigate array effects on the primary turbine, two additional identical turbines were placed
 133 upstream to alter the inflow, as shown in Fig. 3. The hubs of the front turbines were positioned one
 134 rotor diameter ($1D$) upstream and $1.5D$ either side of the primary turbine hub, giving a transverse
 135 separation of $3D$.

136 The flow measurements and loading tests were conducted for three array configurations (AC) as
 137 shown in Fig. 3: AC1 with only the primary turbine installed; AC2 with the front two turbines but not
 138 the primary turbine; and AC3 with the full three turbine array. The location of each specific turbine
 139 was kept constant in all cases. For baseline comparison, flow was measured in the tank without any
 140 turbines installed, shown as configuration AC0 in Fig. 3.

141 The blockage ratio, defined as the turbine blade swept area relative to the tank cross-sectional area,
 142 is approximately 2.3% for each turbine, giving 4.6% upstream blockage to the primary turbine, and
 143 6.8% total blockage for the combined three turbine array. The horizontal dimension of the tank is large
 144 enough that the edges of the tank have a limited impact on the the bypass flow around turbines. The
 145 vertical scale of the rotor diameter to water depth was designed to be similar to that for real turbine
 146 installations [e.g. 29,30], which is important to accurately model the interaction between tidal stream
 147 turbines, as in this study.

148 The local co-ordinate system used for these tests has the origin at the primary turbine hub, with
 149 X positive in the streamwise direction. Distances are normalised by the turbine diameter D of 1.2 m.

Table 2. Description of installed instrumentation and variables measured

Instrumentation	Variables measured	Sample Rate [Hz]
Vectrino Profiler ADV	Velocity components, U, V, W .	100
Bespoke TST Instrumentation	Torque, T , Thrust, Q , Streamwise root bending moment, RBM , Rotational position, θ .	256

150 2.4. Flow measurements

151 Flow measurements were obtained through acoustic Doppler velocimetry using a Nortek Vectrino
 152 Profiler ADV [31] at 100 Hz sample rate. The short-range profiling capability of the instrument was
 153 not used for these tests, with only a single measurement point used. The tank was periodically seeded
 154 with neutrally-buoyant glass micro-spheres to produce and maintain mean correlation between beams
 155 >95%. The velocity range was set to 1.8 m/s to prevent wrapping due to high velocity spikes.

156 For this study, point measurements of flow were taken at various locations to characterise the
 157 inflow, wake, and region between the turbines. All flow measurements were taken at hub height,
 158 1 m (0.83D) above the tank floor. Flow in the tank was allowed to reach steady state before any
 159 measurements were made. A 256 s measurement of U, V, W velocity components was used to
 160 characterise the flow at each point of interest, based on previous experience at FloWave [26].

161 The flow measurement data were processed to remove outlier spikes using the MATLAB
 162 ‘despiking toolbox’ implemented in Mori *et al.* [32] based on the method of Goring and Nikora [33].
 163 The mean value of each 25600 sample flow measurement was taken for the streamwise, transverse,
 164 and vertical velocity components $\bar{U}, \bar{V}, \bar{W}$, with the standard deviation σ_U , and turbulence intensity I_U
 165 (Eq. (2)) calculated for the streamwise component.

$$I_U = \frac{\sigma_U}{\bar{U}} \quad (2)$$

166 Due to time constraints and other investigation priorities, the number and position of flow
 167 measurement points varies slightly between array configurations. It was not possible to measure flow
 168 within 0.3 m of the turbine rotor. Table 2 summarises the specifications of the instrumentation used in
 169 the test programme.

170 3. Influence of turbine arrays on flow conditions

171 The first part of the results investigates the influence of the different turbine array configurations
 172 on the flow conditions in the tank, with a focus on the inflow conditions for the primary turbine. All
 173 flow measurements are taken at hub height, and the turbines were operated at their design speed of
 174 90 rpm for these tests. Flow through the turbine array is influenced by the turbines, therefore rotational
 175 speeds of the turbines are quoted in rpm, rather than tip-speed ratio (TSR), in all the results discussed
 176 in this paper. A nominal TSR can be calculated for reference based on the nominal inflow velocity of
 177 0.8 m/s.

178 3.1. Spatial analysis of flow variation

179 The influence of the turbine arrays on both inflow and wake along the centreline of the array in
 180 the streamwise direction is shown in Fig. 4, for the four configurations described in Fig. 3. For all cases
 181 with turbines in the tank, there is an inflow deficit to the array of 0.05–0.1 m/s (5%–12%) upstream
 182 of $X/D = -1$. This is most pronounced for the three turbine array with a higher overall blockage.
 183 With just the two front turbines in the tank (configuration AC2) the flow velocity at the location of
 184 the rear turbine rotor $X/D = 0$ is similar to the empty tank baseline (AC0). This demonstrates the
 185 flow acceleration between the two front turbines. For the single and triple turbine arrays (AC1 and

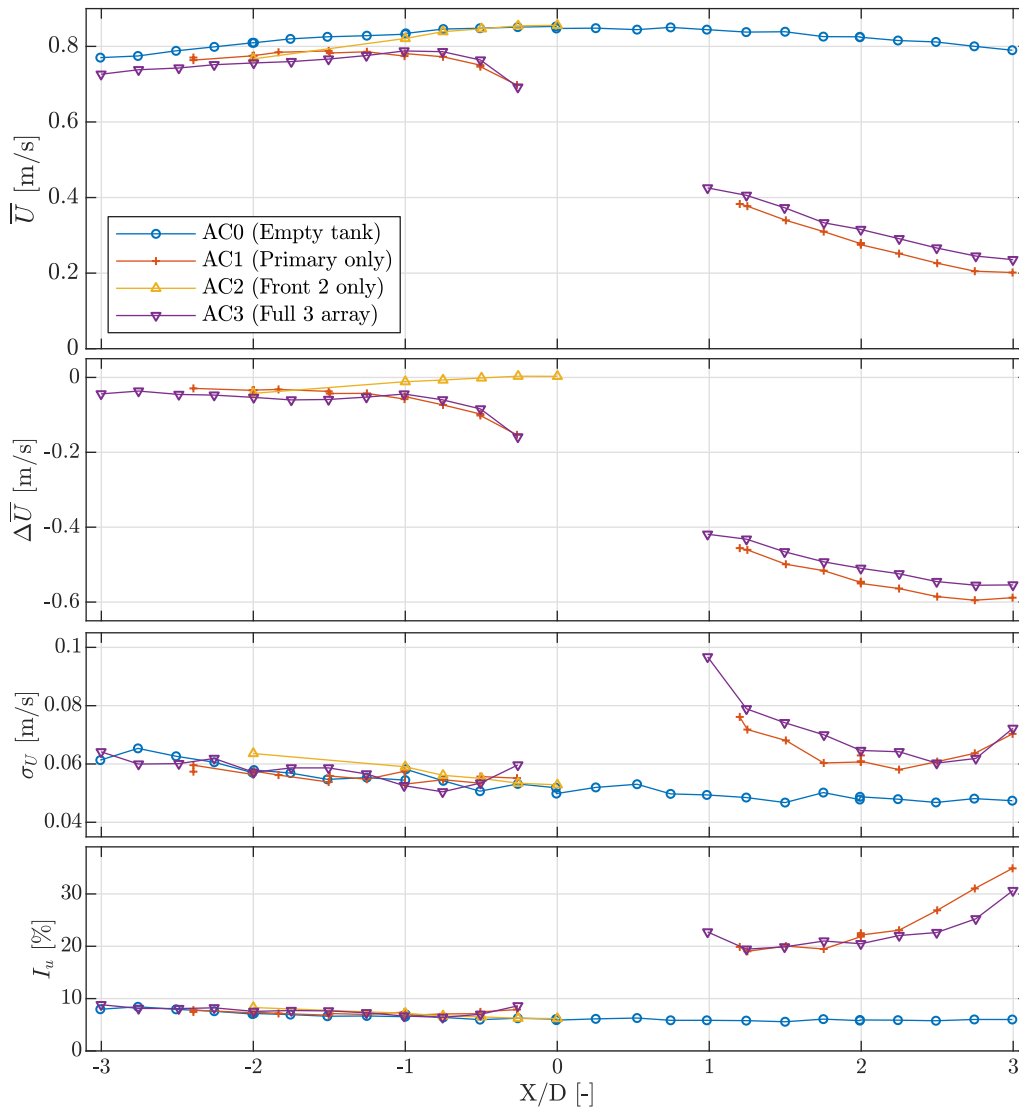


Figure 4. Transect along centreline of array ($Y/D = 0$) at hub height. Sub-panels show mean velocity \bar{U} , mean velocity relative to empty tank $\Delta\bar{U}$, standard-deviation σ_U , and turbulence intensity I_U .

186 AC3) there is a significant wake deficit. For the three turbine array this deficit is reduced, showing the
 187 influence of the increase in flow velocity persisting through to the primary turbine.

188 There is limited impact of the turbines on inflow fluctuations, characterised by σ_U and I_U , which
 189 are similar to the empty tank conditions (AC0). Downstream of the array, the increased turbulence
 190 in the wake is clearly visible in Fig. 4, with $I_U > 20\%$ compared to the empty tank baseline of $\approx 6\%$.
 191 Interestingly I_U appears similar or greater for the single turbine compared to the triple turbine array,
 192 despite increased σ_U for the latter. This can be attributed to the way I_U is defined as a function of flow
 193 velocity (Eq. (2)), and the reduced wake deficit for the triple turbine array.

194 Due to the re-circulation of currents at FloWave [22,23], consideration was given to blockage in
 195 the tank and how this affects the flow re-circulation. Figure 5 shows the wake of a single turbine as a
 196 function of rpm, with more blockage and higher wake deficit at higher rpm, as would be expected.
 197 The inflow does not show a significant variation with rpm however, suggesting that the wake deficit
 198 has fully recovered in the return path through the impellers. A similar situation is shown in Fig. 4,
 199 where the wake for a single turbine is slower than for the three turbine array but the inflow is of similar
 200 magnitude.

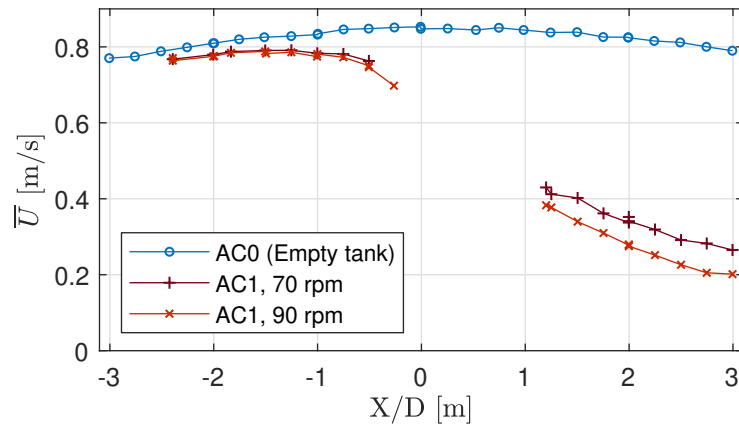


Figure 5. Transect along primary turbine centreline ($Y/D = 0$), showing inflow and wake at varying rotational speed for configuration AC1, with AC0 for comparison.

201 To investigate the flow regime in the region between the turbines, a grid of flow measurements
 202 were made with spacing $X/D = 1/4$ and $Y/D = 1/2$. This is shown in Fig. 6 as both XY vectors and
 203 U, V, W components. The flow is relatively straight and uniform for most of the measurement locations
 204 and array configurations, however a number of interesting effects are present.

205 Considering first streamwise velocity U . Comparing AC1 to AC0, the upstream blockage
 206 (induction region) from the single turbine is clearly visible with a reduction in flow $> 5\%$ at all
 207 measurement points, even at $X/D = -1, Y/D = \pm 1$. For AC3, the presence of the primary turbine leads
 208 to a faster flow at $Y/D = \pm 1$ compared to AC2 due to local bypass flow.

209 The flow of water around the turbines is visible in the transverse component V . The outwards flow
 210 around the primary turbine can be seen in AC1 and AC3, while recovery of the inward constriction
 211 between the front two turbines is apparent in AC2 and AC3. With no obstructions from the rear turbine
 212 in AC2 the flow is relatively straight $> 1D$ downstream of the blade tips.

213 The three-dimensional rotating wake vortex of the front two turbines is apparent in the vertical
 214 flow component W at $Y/D = \pm 1$ for cases with them installed (AC2 and AC3) compared to those
 215 without (AC0 and AC1). As all three turbines rotate in the same direction, anti-clockwise when looking
 216 at the rotors from upstream, the wake vortices shed from either side are opposing. At $Y/D = 1$ this
 217 results in the wake being forced down, resulting in W becoming more negative for AC2 and AC3.
 218 Conversely, at $Y/D = -1$, W is more positive, co-incidentally cancelling out the slight downward trend
 219 seen at this location in the empty tank (AC0).

220 The slight asymmetry in magnitude of these effects may result from a number of factors: the
 221 off-centre array location, an artefact of the rotating turbines, and/or it may be a slight misalignment
 222 (~ 10 mm) of the velocity measurement points with respect to the blade tips.

223 3.2. Frequency domain analysis of spatial flow variation

224 Frequency domain analysis enables a more detailed assessment of the nature of the flow
 225 disturbance induced by the turbines. As detailed in Section 3.1, the introduction of the front two
 226 turbines results in significant changes to the magnitude, direction, and variability of the flow. The
 227 presence of the turbines are also expected to introduce flow disturbances corresponding to multiples
 228 of the rotational speed, which may subsequently influence the loading on the primary turbine. The
 229 frequency domain analysis presented in this section assesses this, and is carried out using a Fast
 230 Fourier Transform (FFT) applied to the U, V and W velocity components at various spatial locations.

231 Examples of the frequency domain flow outputs are presented in Fig. 7. This figure shows the
 232 U velocity components for AC3 (see Fig. 3), at three streamwise positions and at three transverse
 233 positions (where data exists). It is evident that the upstream velocity does not contain any frequency
 234 content corresponding to the rotational speed of the turbine, $1p$, whereas immediately downstream

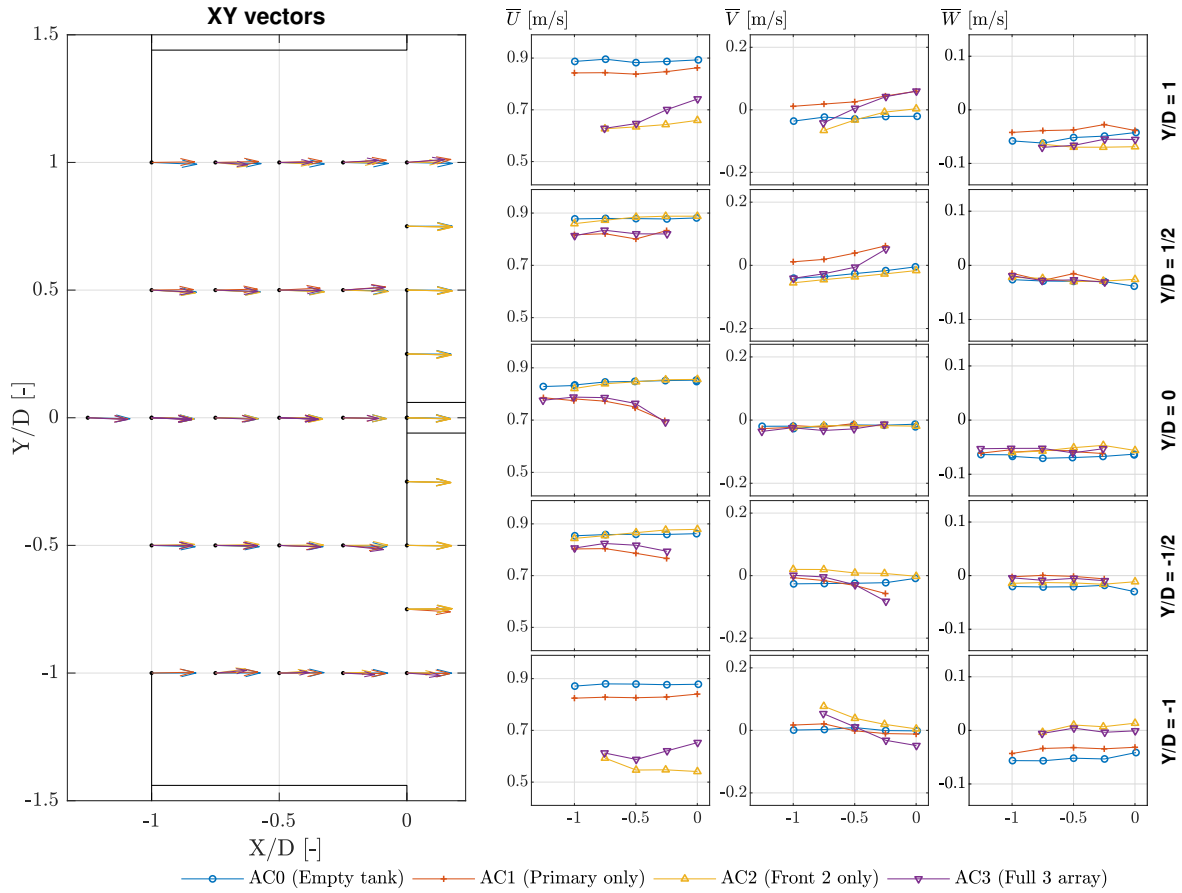


Figure 6. Variation of flow between turbine locations. Subplots show (left) XY velocity vectors relative to turbine/blade positions, and (right) \bar{U} \bar{V} \bar{W} at points on five streamwise transects. For details of array layout and configurations tested see Fig. 3.

235 of the front two turbines ($X/D = -3/4$) there is significant energy content at $1p$, $2p$, $3p$ and $6p$. These
 236 appear to dissipate quickly downstream, and at $X/D = -1/4$ these components are no longer significant
 237 or visually discernible. Immediately in front of the primary turbine ($X/D = -1/4$) a peak at $1p$ is
 238 present, which due to the rapid decay of rotation-induced fluctuations downstream of the front two
 239 turbines, appears to be flow variation resulting from the primary turbine itself.

240 Also apparent in Fig. 7 is a small, broad, peak centred at around 4.7 Hz for some of the
 241 measurements. This peak, which is rather unfortunately close to $3p$, appears to be intermittent
 242 vibration of the ADV mounting. Care must therefore be taken not to confuse this vibration with $3p$
 243 velocity content. The narrow banded and large peaks associated with $3p$ content facilitate this.

244 To assess the spatial variability of rotation-specific frequency components, a metric has been
 245 defined. This enables a single number to describe the relative frequency content at multiples N of the
 246 rotational frequency p for each velocity component. This metric k is defined as follows:

$$k_{\bar{u}, Np} = \frac{\int_{Np-\delta f}^{Np+\delta f} S_{\bar{u}}(f) df}{\int_0^{\infty} S_{\bar{u}}(f) df} \quad (3)$$

247 where $S_{\bar{u}}$ is the energy spectrum of velocity vector $\bar{\mathbf{u}}$, and δf is half the width of the bin used for
 248 integration. This δf has been chosen to allow for slight rotational speed variations, whilst ensuring
 249 the energy resulting from the aforementioned ADV vibrational peak at 4.7 Hz is omitted. A value of
 250 0.03 Hz was utilised.

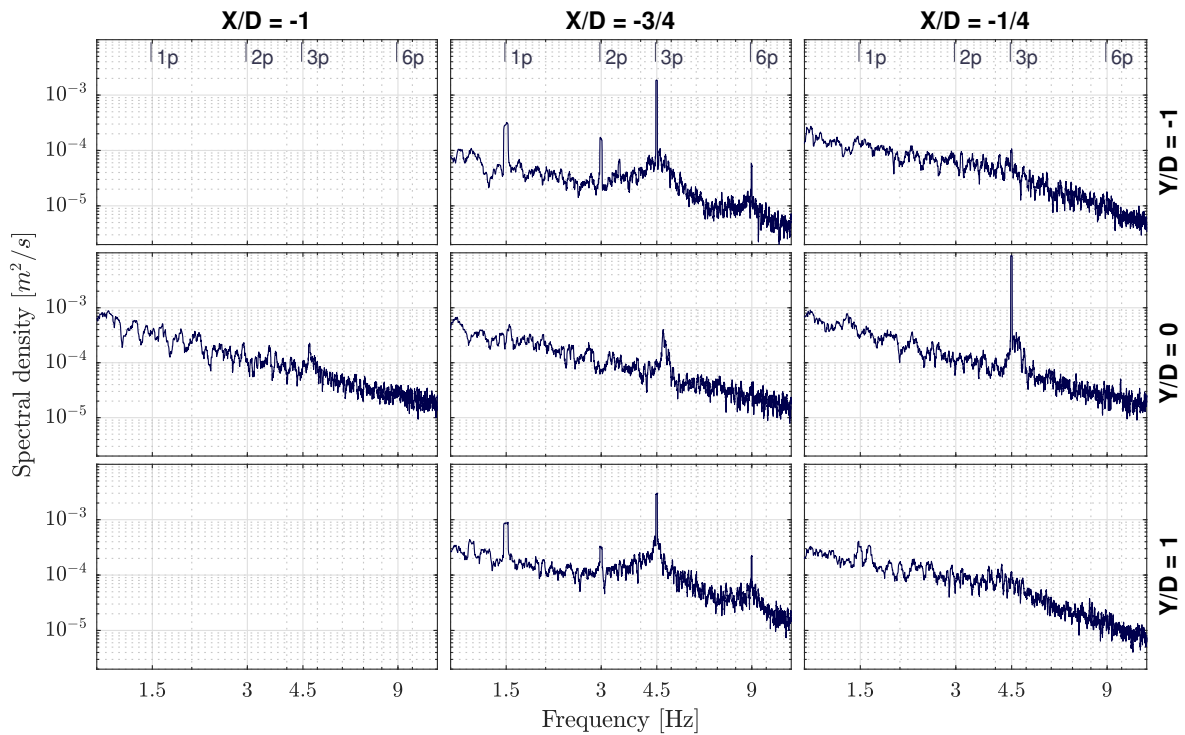


Figure 7. Example spectral density plots for streamwise velocity component U at seven positions for configuration AC3 with all three turbines operating at 90 rpm.

251 The metric defined in Eq. (3) has been applied to all data corresponding to points presented in
 252 Fig. 6, with all turbines operating at 90 rpm. The resulting spatial variation of $k_{\bar{U},3p}$ is shown for U , V
 253 and W components in Fig. 8 for array configurations AC0, AC1, AC2 and AC3. Assessing Fig. 7 along
 254 with the U component of Fig. 8, it is evident that the metric defined in Eq. (3) is describing the relative
 255 magnitude of peaks at multiples of the rotational speed well.

256 As noted in Fig. 7, it is observed that there is an increase in $1p$, $2p$, $3p$ and $6p$ velocity content in
 257 U behind the front turbines: $Y/D = \pm 1$. This decreases rapidly with increasing X indicating that the
 258 dissipation rate is high. This is also evident in Fig. 8 and occurs for U , V , and W components hinting
 259 at the three-dimensional nature of the tip vortex structures. The magnitude of the $3p$ content is shown
 260 to be comparable behind both of the front two turbines. Assessing $Y/D = \pm 0.5$ and $Y/D = 0$, it is clear
 261 that this disturbance does not propagate significantly in the transverse direction and hence does not
 262 affect the downstream turbine.

263 As mentioned, in Figs. 7 and 8 there is the appearance of significant $3p$ peak in U immediately in
 264 front of the primary turbine ($X/D = -1/4$) when all three turbines are present (AC3). Assessing the two
 265 turbine equivalent (AC2) in Fig. 8, it is confirmed that this is a result of the primary turbine itself, and
 266 is an upstream velocity disturbance associated with the passing of each blade. It is evident that this $3p$
 267 velocity fluctuation is a result of the varying pressure field induced by each blade pass, yet it remains
 268 unknown why this effect is observed directly in front of the nacelle for AC3 and not AC1. The authors
 269 speculate that this may be a result of this effect being highly spatially variable, coupled with minor
 270 sensor position discrepancies, $O(10\text{ mm})$, between AC1 and AC3 measurement programmes.

271 4. Influence of turbine array on loading and power

272 The second part of the results considers the effect of the turbine array on the loads experienced
 273 and power extracted by the primary turbine. This is achieved by comparing the single turbine to the
 274 triple turbine array (configurations AC1 and AC3). For these tests the front two turbines were operated
 275 at 58 rpm, 70 rpm, and 90 rpm (nominal TSR of 4.5, 5.5, and 7 respectively). For each of these cases, the

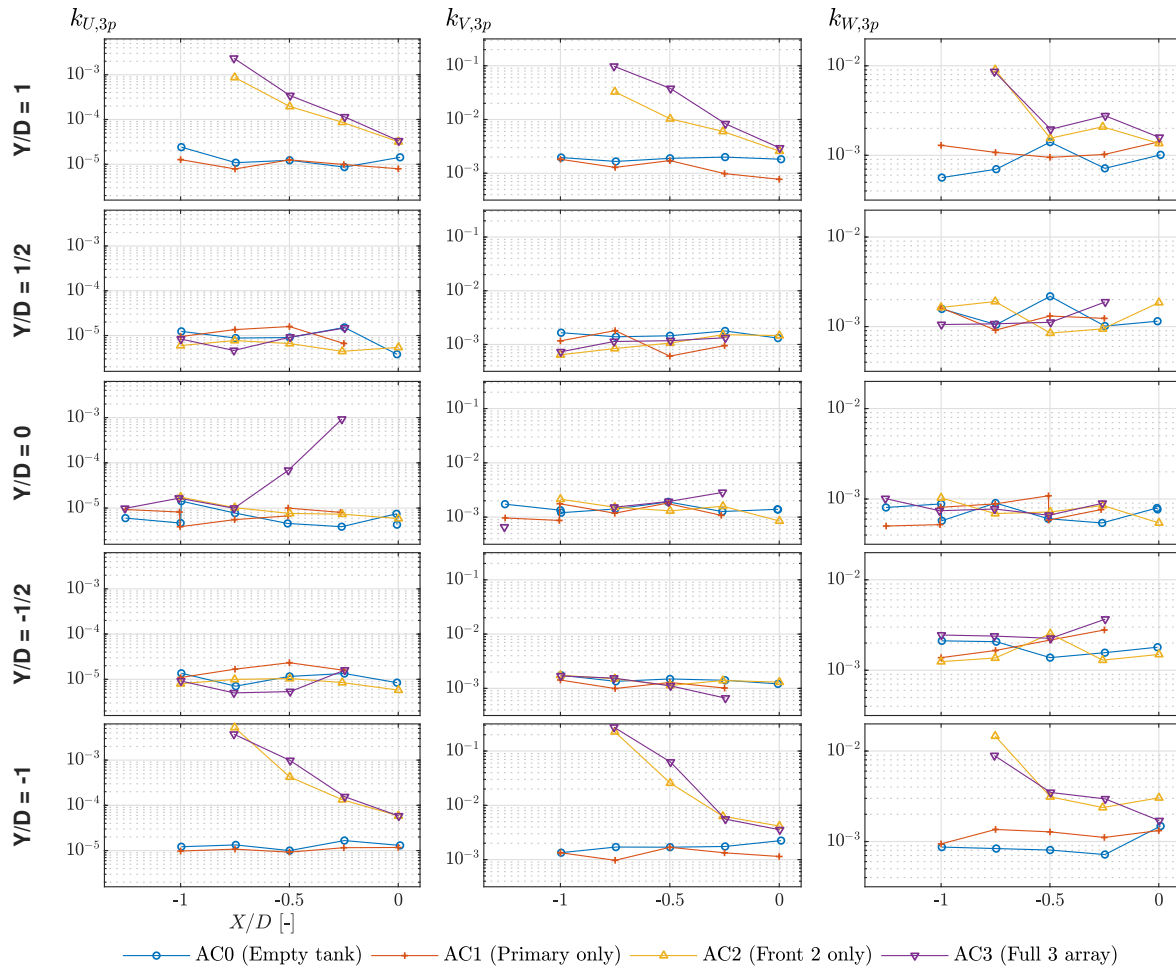


Figure 8. Relative energy content (defined by Eq. (3)) at three times the rotational speed in U, V and W velocity components for various spatial locations. Shown for all array configurations defined in Fig. 3.

276 primary turbine was operated at a range of rotational speeds ranging from 58 rpm to 104 rpm (8 points
277 in total).

278 4.1. Time-domain turbine response

279 Figure 9 shows the mean thrust, power and root bending moment of one of the blades of the
280 primary turbine as a function of rotational speed of the primary turbine. Curves from the single
281 turbine case have also been plotted for comparison. It was not possible to use normalised quantities
282 (like C_p , C_t and TSR) due to difficulty in selecting a nominal flow velocity for the array owing to the
283 modification of inflow velocities by the array.

284 It is evident from Figure 9 that the presence of the front row of turbines increases the flow velocity
285 experienced by the primary turbine (as discussed in Section 3.1). This subsequently causes an increase
286 in the loads experienced. Operating the front row turbines at higher rotational speeds increases the
287 blockage, further increasing the velocity along with the measured power, thrust and RBM. Hence,
288 when the front row turbines are operated at 90 rpm the largest values are recorded. Around the
289 optimum power operating point (70–84 rpm) the thrust experienced by the primary turbine and the
290 RBM of the turbine blade were 4.8%–7.3% and 4.0%–6.7% higher respectively when operating in
291 the array with the front row turbines operating at 90 rpm. For both thrust and RBM increasing the
292 rotational speed of the primary turbine serves to increase the mean load along with the standard
293 deviation. The increase in the mean loads clearly indicates increased inflow velocities experienced
294 by the primary turbine when operating in the array (AC3) when compared to the single turbine case

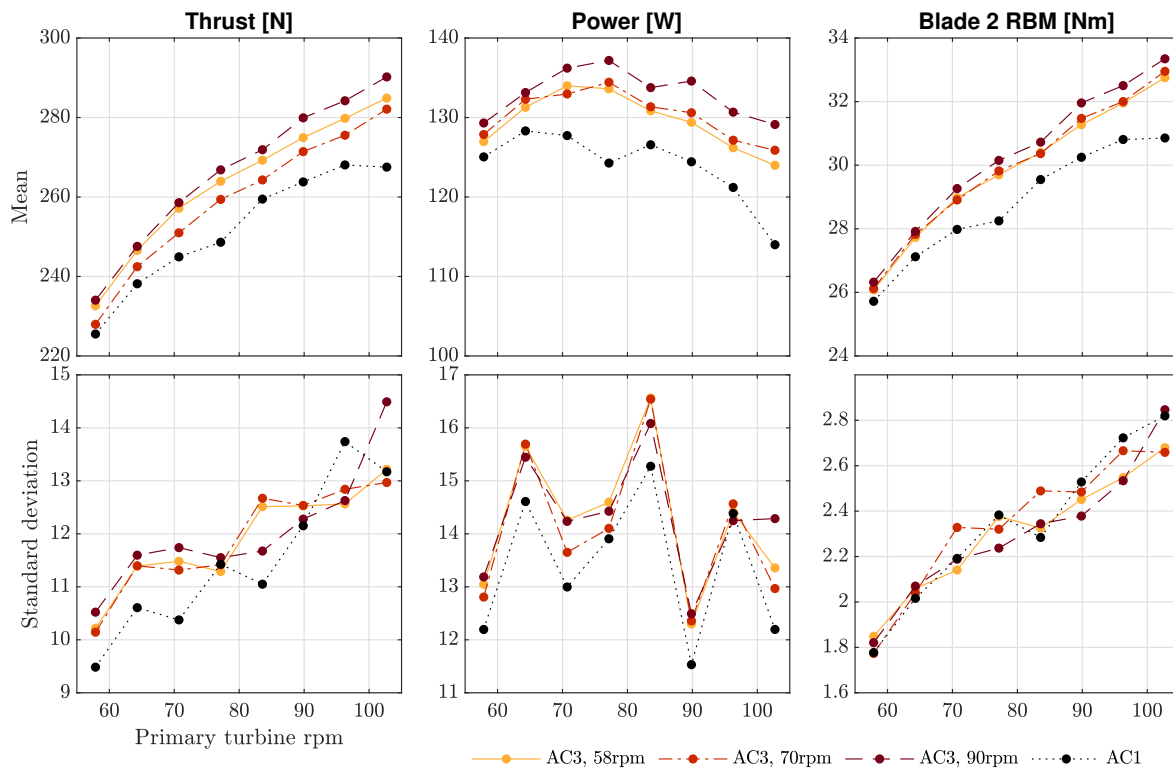


Figure 9. Average and standard deviation of thrust and power of the turbine plus root bending moment of a blade all as a function of rotational speed. Each plot shows these forces/moments for the primary turbine with the front two turbines operating at three different rotational speeds (AC3) and also shows the comparable single turbine case (AC1).

295 (AC1). This is not directly seen in Figure 4, where the inflow velocity measured at hub height in the
 296 AC1 and AC3 cases are similar. This figure only shows single point flow velocity measurements made,
 297 which do not give full information of the inflow velocities seen by the whole rotor.

298 The power curves follow the standard power versus speed curve of the turbine (see [19]). Owing
 299 to the higher flow velocities (and slightly higher C_p values), the power extracted by the main turbine
 300 is significantly higher when in the array. The power extracted by the primary turbine increased by
 301 5.7%–10.4% when in the array with the front row turbines operating at 90 rpm. The measured power
 302 curve of the main turbine is higher with the front row turbines operate at 90 rpm than at 58 rpm or
 303 70 rpm. The difference in the power extracted is not significant between the two lower rotational
 304 speeds.

305 The measured thrust, power and blade RBM are tabulated in Table 3 for selected cases. Values are
 306 given both for the model-scale measurements and at full-scale equivalent, based on the nominal 1:15
 307 scale factor of the turbine.

308 4.2. Frequency-domain turbine response

309 In this section, the loads experienced by the rotor and the blades of the single turbine and the
 310 array cases (AC1 and AC3), are compared in the frequency domain through spectral density plots of
 311 the measurements made.

312 Figure 10 shows the spectral density plots of the thrust and the blade RBM with all turbines
 313 operating at 90 rpm for AC3 and AC1. There are peaks in the plots that correspond to physical
 314 events during turbine rotation. In the spectral density plot of the blade RBM, the main peak is at $1p$
 315 (occurring once per revolution) and corresponds to tower shadow effect and velocity shear. This $1p$
 316 peak amplitude is higher than the low frequency turbulence induced load. Further peaks at $2p$ and $3p$

Table 3. Thrust and power of the turbine plus root bending moment of a blade for selected rotational speeds. Values given for model scale and full scale equivalent.

Array Config.	Front turbines rpm	Primary turbine rpm	Measured model scale (0.8 m/s)			Full scale equivalent (3.1 m/s)		
			Thrust [N]	Power [W]	Blade RBM [Nm]	Thrust [kN]	Power [MW]	Blade RBM [MNm]
AC1	—	58	225.5	125.0	25.72	761.1	1.635	1.302
AC1	—	70	244.9	127.7	27.98	826.6	1.670	1.417
AC1	—	90	263.8	124.4	30.25	890.3	1.626	1.531
AC1	—	104	267.5	114.0	30.86	902.9	1.490	1.562
AC3	58	90	274.9	129.4	31.27	927.9	1.691	1.583
AC3	70	90	271.4	130.6	31.47	916.1	1.707	1.593
AC3	90	58	234.0	129.3	26.32	789.9	1.690	1.333
AC3	90	70	258.6	136.2	29.27	872.7	1.780	1.482
AC3	90	90	279.9	134.6	31.96	944.7	1.759	1.618
AC3	90	104	290.2	129.1	33.35	979.5	1.688	1.688

are seen, which are harmonics of the $1p$ peak, which can be explained by the azimuthal variation of the RBM of the blades discussed and shown in Payne *et al.* [16]. In the spectral density plot of thrust, the $3p$ peak has the highest amplitude and corresponds to the $1p$ peak observed in the RBM. The amplitudes of the peaks at $6p$ and $9p$ decrease with increasing frequency and, therefore, indicate that they are harmonics of the $3p$ peak. The $12p$ peak is due to motor cogging effects, introduced by the 12-pole motor used in the turbine, while the $24p$ peak is its second harmonic. A small peak at $1p$ is seen, which was also seen with the turbine tested in the dry, which is most likely due to some mechanical artefact (for example some misalignment in the drive train). For clarity on Fig. 10 only the case with the front turbines operating at 90 rpm is shown. The plots for AC3 at all front turbine rotational speeds tested (58 rpm, 70 rpm, and 90 rpm) are very similar.

Comparing the array and single turbine cases (AC3 and AC1), the difference in the spectral density plots is extremely small. Note that due to the log scale being used, the differences between the plots in the high frequency range seem to be magnified, but are small relative to the net energy content of the signal. The spectral density plot of turbine thrust show smaller peaks at the $9p$, $12p$ and $24p$ frequencies for the single turbine (AC1) when compared to the array (AC3).

5. Discussion

Using larger-scale models in a laboratory environment facilitates measurement that increases understanding of the complex flow conditions around the array of turbines on test, because environmental conditions can be repeatably controlled as required and unwanted scale effects are minimised. The relatively larger physical size of the turbine also permits the inclusion of more comprehensive measurement instrumentation.

As noted in Section 2.3, numerical BEM-CFD modelling [34] has shown that a staggered array with 3D lateral spacing between the front turbines increases flow speed and thus power produced by the rearmost turbine. The results of the physical modelling described in this paper substantiates this finding. The tests also provide valuable insight into the loading experienced by the rear turbine, both in the closely-spaced staggered array configuration that may be compared to measurements made on one unit on its own.

The increased flow speed seen by the rear turbine in this closely-packed staggered array offers some performance and economic benefit in terms of increased power generation. The upstream turbine wakes, and associated turbulence, do not appear to directly influence the loading on the downstream turbine. This is evidenced by the spectral analysis of the velocities and turbine loads, and supports the conclusions made for much larger downstream separations in [13]. The reduction in wake deficit seen

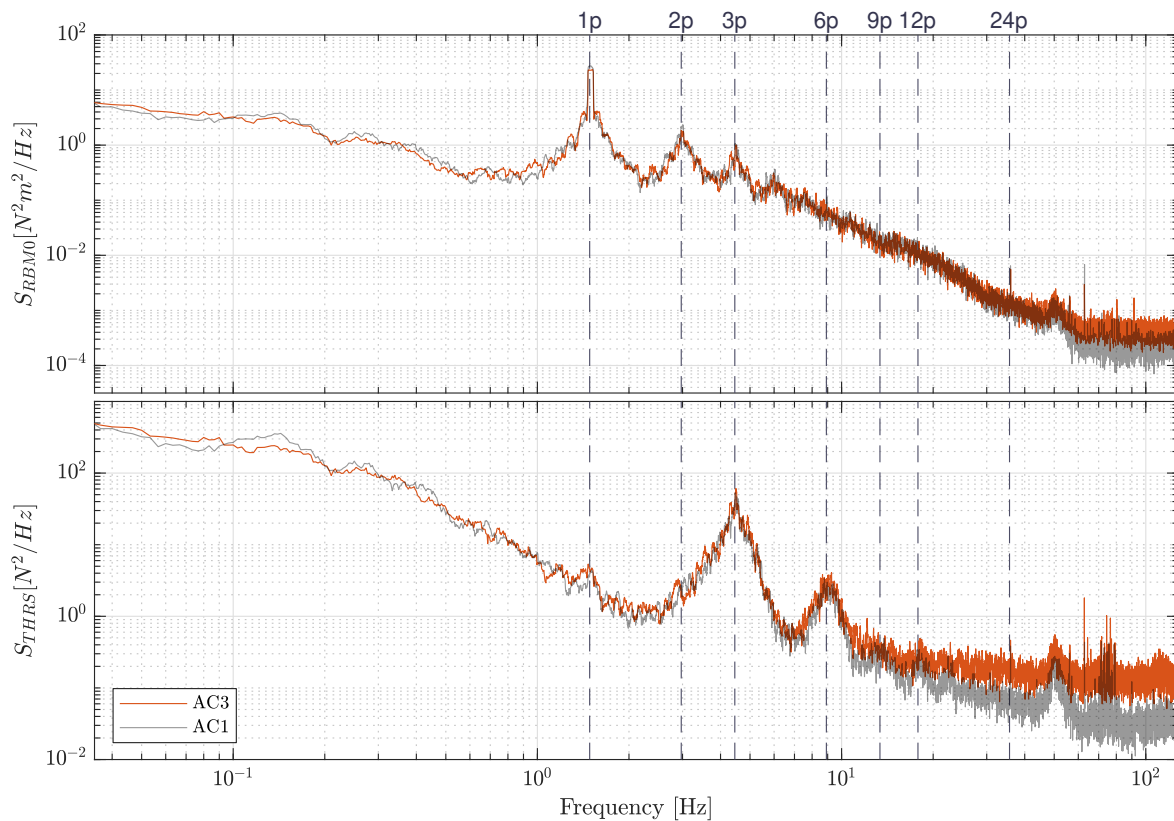


Figure 10. Spectral density plots of the thrust and the blade root bending moment experienced by the primary turbine, with the front two turbines (AC3) and from the single turbine case (AC1). All turbines operating at 90rpm.

349 for the primary (downstream) turbine may also lead to an increase in power for subsequent rows of
 350 turbines, however additional (numerical) modelling would be required to test this hypothesis.

351 Constructing a closely-packed array, as simulated in this work, offers the prospect of more
 352 efficient use of the seabed and a slight reduction in the extent of interconnecting cabling, compared
 353 to an installation with more typical 10–15 diameter spacing between rows of turbines. Access for
 354 installation, operation, and maintenance activities may however be more complex.

355 The influence of incident flow angle relative to the axis of the turbine array was not assessed,
 356 as most deployments are expected to be aligned with the predominant direction of flow of the tidal
 357 current. Over the full tidal cycle the changing direction of flow will vary the angle of incidence on the
 358 array. This could be an interesting case to explore, however, as even in the ‘design’ direction there may
 359 be an increased influence of a front-row turbine on those behind, a factor of both the flow angle and
 360 array geometry. In addition, there may be asymmetrical flow acceleration between the front turbines,
 361 leading to more complex loading on the rear turbine. It will be prudent to simulate these situations
 362 numerically before performing additional tank tests for validation.

363 6. Conclusions

364 The results of the experimental work presented show, for the first time, results from three
 365 larger-scale instrumented tidal stream turbines in a closely spaced staggered array. Most significantly,
 366 modification of the flow field resulting from the presence of upstream turbines, and the consequent
 367 acceleration of inflow to those downstream influences both the loading of, and power produced by, the
 368 downstream turbines. This will help inform the design and optimisation of the layout of tidal turbine
 369 arrays.

Specifically, this work has shown that the addition of two upstream turbines increases both the power and thrust acting on the downstream turbine, irrespective of the rotational speed of the turbines. Increasing the rotational speed of the front row serves to further increase the power developed by the rear turbine due to the higher resulting effective blockage. At the peak power operating point the mean power of the rear turbine is observed to increase by 5.7%–10.4% with a corresponding increase in mean thrust of 4.8%–7.3%. Through statistical and frequency-domain analysis of the flow measurements and turbine loads it may be concluded that this increase in power does not come at the expense of increased unsteady loading from the wake induced by the upstream turbines.

The experimental results presented in this paper represent the first large-scale experimental tests of a closely-spaced array of three tidal turbines, and validate findings from numerical models to provide new insight into the associated flow field and turbine performance and loading. Additionally, two corresponding datasets [35,36] from these physical model tests are available to others to provide valuable assistance when calibrating and validating numerical models of tidal stream turbine arrays.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Array Configuration
ADV	Acoustic Doppler Velocimeter/Velocimetry
FFT	Fast Fourier Transform
RBM	Root Bending Moment
TSR	Tip-Speed Ratio

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