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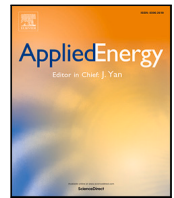
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The influence of waves propagating with the current on the wake of a tidal stream turbine

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ABSTRACT

The presence of the wind-waves enhances the flow turbulent complexity and modifies the dynamic behaviour of the tidal-stream turbine and causes extra challenges for its performance and survivability. A sign of these effects is the modification of the turbine wake under the action of wind-waves, thus assessing the resulting wake characteristics is fundamental for technological development of such devices in single or array configurations. Laboratory experiments, involving regular waves propagating with the current, were conducted to describe the wake structure of a fixed scale model tidal-stream turbine. In order to highlight wave effects, the laboratory measurements are analysed in term of: (i) time-mean velocity profiles, (ii) swirl numbers, (iii) turbulence intensities and (iv) turbulent anisotropy maps. In each case, distinctive features are discussed in the downstream rotor near and far fields. The velocity profile is slightly affected by the waves in both near and far fields. The swirl number in the near field is drastically influenced by waves presence where a significant correlation with the wave-steepness is highlighted. Wave presence also affects the turbulence intensities both in the near and far field. This phenomenon is more evident at the top-tip and rotor-centreline water depth instead of in the bottom-tip level. The analysis of turbulent anisotropy maps shows that waves act on the wake flow leading to axisymmetric turbulent conditions mainly dominated by the axial turbulence component. These results constitute an initial step toward the understanding of unsteady wake interactions, in arrays of tidal stream turbines.

1. Introduction

Human society is largely dependent on fossil fuels for the provision of energy. In China [1] and the European Union [2], 71.1% and 42.6% of 2018 electricity generation was provided by fossil fuels. In general, fossil fuels reserves are depleting, and new reserves are becoming harder to locate. Moreover, extracting and burning the fossil fuels causes several environmental impacts such as land degradation, water pollution and emissions. In case of carbon dioxide, the abundance of this chemical component traps heat in the atmosphere thus activating a process that in turn plays a role in the global warming trend [3]. In this scenario, developing the renewable energy sector is recognized to be of fundamental importance for the future of the human society [4].

Among the different renewable energies, marine renewable started attracting the interest of the research sector for decades but more

recently an increasing interest in the harvesting of marine renewable is noticeable [5]. In this context, the tidal energy is one of the different marine renewable energies. This kind of energy can be harvested by tidal range technologies or tidal stream technologies. The commercial technology for harvesting the tidal range energy, also said the tidal barrages, dates back in 1966 when a first plant was built in France and it is still in operation. Decades of continuing functioning proved that this technology is robust enough (according to EDF Groups [6]), but probably due to high capital costs and environmental impacts the interest of developers is currently mainly focused on tidal stream technologies such as the horizontal-axis turbines, vertical-axis turbines or hydrofoils [7].

Acquiring an efficient technology for harvesting the kinetic energy of tidal streams will permit to explore the huge availability of this

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Nomenclature

α	Aspect ratio (–)
ΔU_x	Streamwise velocity deficit (m/s)
δ	Thickness of the wake shear layer (m)
δ_{ij}	Kronecker delta (–)
η, ξ	Independent invariants of anisotropy tensor (–)
κ	von Kármán constant (–)
λ_i	The eigenvalues of the Reynold-stress tensor (–)
ν	Kinematic viscosity of water (m ² /s)
ω_a	Absolute angular frequency of waves (rad/s)
ω_r	Angular velocity of rotor (rad/s)
ρ	Water density (kg/m ³)
σ	Standard deviation of velocity (m/s)
τ	Time lag of integral scale (s)
θ	Twist angle of blade section (deg)
A	Swept area of rotor (m ²)
b	Reynold-stress anisotropy tensor (–)
c	Chord length of blade section (m)
C_1	mPST-SH auto-safe level (–)
C_2	mPST-SH auto-exclude level (–)
C_p	Power coefficient of the turbine (–)
C_t	Thrust coefficient of the turbine (–)
C_{group}	Group velocity of the wave (m/s)
C_{phase}	Phase velocity of the wave (m/s)
D	Diameter of the rotor (m)
E_w	Wave energy density (J/m ²)
F	Thrust on the rotor (N)
Fr	Flume Froude number (–)
g	Gravitational acceleration (m/s ²)
H	Wave height under wave-current condition (m)
h	Depth of the measurement water volume (m)
H_0	Wave height under wave-alone condition (m)
k_0	Wave number under wave-alone condition (m ^{–1})
k_w	Wave number under wave-current condition (m ^{–1})
L	Wavelength under wave-current condition (m)
l	Length of the measurement water volume (m)
L_0	Wavelength under wave-alone condition (m)
m_0	Variation of wave elevation (m ²)
P_w	Wave energy density flux (W/m)
R	Radius of the rotor (m)
r	Radius from the centre of blade (m)
r_τ	Auto-correlation of with time lag τ (–)

r_δ	Radius from the maximum velocity gradient position (m)
Re	Blade-tip Reynold number (–)
S_w	Swirl number of the wake (–)
T	Time period of the absolute observer (s)
t	Thickness of the blade section (m)
T_x	Integral time scale of streamwise velocity (s)
TI	Turbulent intensity (–)
U^*	Friction velocity (m/s)
U_0	Bulk velocity of the incoming flow (m/s)
U_r	Ursell number of the wave (–)
U_T	Blade-tip tangential velocity (m/s)
U_t	Tangential velocity (m/s)
U_x	Mean longitudinal velocity (m/s)
U_y	Mean transverse velocity (m/s)
U_z	Mean vertical velocity (m/s)
U_0^c	Bulk velocity of the incoming flow under current-only condition (m/s)
w	Width of the measurement water volume (m)
X	Normalized longitudinal coordinate (–)
x	Longitudinal coordinate (m)
Y	Normalized transverse coordinate (–)
y	Transverse coordinate (m)
Z	Normalized vertical coordinate (–)
z	Vertical coordinate (m)
z_0	Distance from the flume bed (m)
COR	Correlation coefficient (–)
SNR	Signal-noise ratio (–)
TSR	Tip-speed ratio (–)

renewable source. For instance, tidal stream energy resources in China could provide more than 13 GW [8] and the maximum peak tidal flow is concentrated in relatively small regions around the Zhoushan islands [9] while EU potential of tidal stream energy is mainly sited in the northern EU seas where, e.g. up to 3 GW is extractable from UK waters only [10].

Among different technologies for the harvesting of tidal range and stream energy (e.g., HATT, VATT, kite, hydrofoil, sail, contra rotating, etc.), horizontal-axis tidal-turbine (HATT) is emerging as dominant technology. In fact, the first commercial tidal-stream array based on HATT has already been built and entered in operation in 2018 [11]. However, horizontal-axis tidal stream turbines are still plagued by several problems (e.g., power fluctuation under complex hydrodynamic environments [5], unbalance loads on the blade [12] etc.), the solution of which still need fundamental and technological research.

The relatively good predictive capacity of the ocean tide models has been recognized and thought of as a key factor in its progression, particularly for the tackling of other renewable energies intermittency, such as solar and wind [7]. Today, the technology is not cost justified but limited to high-turbulent, high-speed flows in shallow sites (< 30–40 m) with depths ranging from 3 to 6 times the turbine radius [24]. To increase the share of the energy mix and reduce costs, many experts envision the deployment of arrays of horizontal-axis tidal stream turbines, called farms; although other factors can play a role, such as public opinion, imposition of carbon taxes, and newer technological advances in the offshore sector. But perhaps, the key to the tidal farm's long-term effectiveness is the maximization of its performance [25], known to be dependent on the local flow impinged on each turbine, and this in turn, is dependent on the downstream flow (wake) of the upstream turbines.

Tidal stream turbines operate in turbulent flows where the presence of wind-waves is the rule rather than an exception and it in turn creates a rough environment with specific turbulence characteristics that affect the turbines performance and survivability features [26]. In the last years, in order to investigate the turbine's behaviour in turbulent flows, several laboratory-scaled model experiments were performed in recirculating flumes and towing-tanks. Special focus is given in the turbine's influence with installation depth [27]; bed roughness [28]; yaw angle [29], inflow velocity [30] and ambient turbulence intensity [31].

The presence of wind-waves in conjunction with a tidal stream affects the turbine performance and in turn modify the turbine's wake [24]. In this perspective, deepening our knowledge on the characteristics of the wake in presence of waves is fundamental for understanding the challenges in the further development of such technology once installed in isolated or array configuration [13].

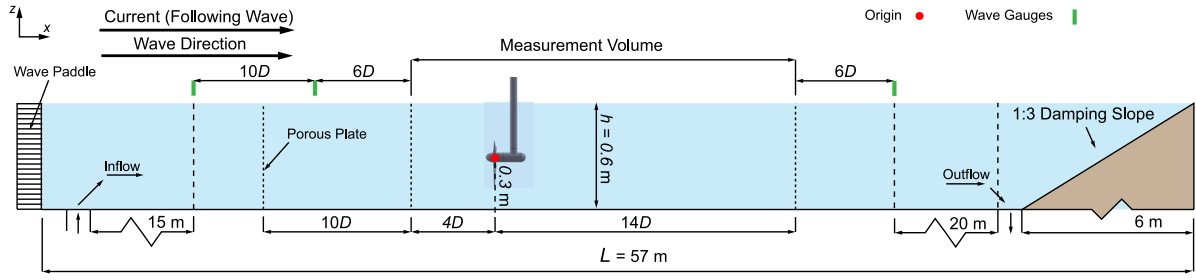
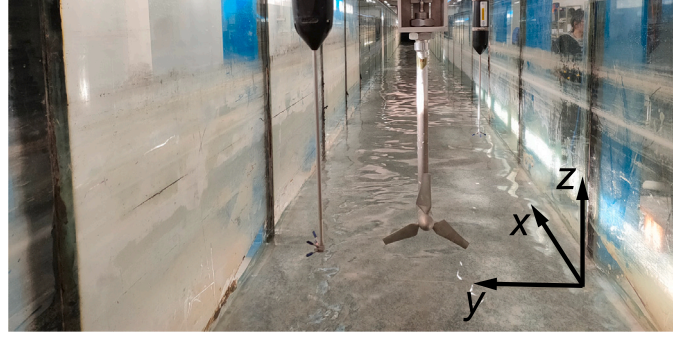
Table 1
Experimental findings of a tidal stream turbine operated in wave–current flows.

Author (Year)	Rotor diameter (m)	Water depth (m)	Blockage ratio (%)	Incident velocity (m/s)	Turbulence intensity (%)	Conclusions of the interactions between wave and tidal turbine wakes
Stallard et al. [13] (2013)	0.27	0.45	2.5–12.7	0.47	8–10	The mean wake is not altered, even though the velocity fluctuation is more than twice in the upper depth.
Gaurier et al. [14] (2013)	0.9	2	8.0	0.1–2.2	5	The wave influence is significant and must be included for the life assessment of turbine parts.
Lust et al. [15] (2013)	0.8	4.9	1.3	1.68	(Towing)	Mean values of C_p and C_T are not dependent on wave form but the variations of C_p may be on the same order of its magnitude.
Luksa et al. [16] (2013)	0.46	1.5	4.6	0.6	(Towing)	The turbine will encounter wave influence throughout depth profile and contribute to enhance the shear effect in boundary layer.
de Jesus Henriques et al. [17] (2014)	0.5	0.76	18.5	0.5	2	Performance fluctuation is increased with waves, altering the statistics of the thrust and power
Galloway et al. [18] (2014)	0.8	1.8	7.5	0.9	(Towing)	The load is related with the parameters of the waves, particularly more of frequency than of height.
Fernandez-Rodriguez et al. [19] (2014)	0.27	0.46	2.5	0.46	≈ 12	In turbulent wave-induced flow, the wave speed contains a few harmonics.
Guo et al. [20] (2018)	0.8	3	< 3	0.56, 0.68	(Towing)	The peak thrust and torque under waves can be as much as 1.5 times its average value
Martinez et al. [21] (2018)	1.2	2	≈ 2.26	0.8	–	The peaks frequencies in the power spectrum density of C_T and C_p associated with waves at 45° and 315° have similar magnitude which proves that these wave directions are symmetrical with respect to the rotor axis.
Draycott et al. [22] (2019)	1.2	2	≈ 2.26	0.8	–	A higher wave height and lower frequency imposes greater power fluctuations in the current flow following with the waves.
Zang et al. [23] (2019)	0.27	0.55	8.7	0.35	10	The wave-induced turbulence imposes greater changes in the integral scale than the rotor rotation.

Laboratory experiments on tidal stream turbine scaled model are the fundamental methodology for the conduction of studies on the performance [32] and wake dynamics [33]. Moreover, most of the time turbine models are built as simple porous discs that aim to exert on the flow a thrust similar to the one exerted by the rotor. However, a fixed porous disc cannot reproduce the swirl in the flow that is due to the dynamical behaviour of a rotor [34]. It is thus questionable, in principle, the use of such laboratory technique once the objective is to study the turbine wake feature [35]. Actually, as reviewed by Zhang et al. [36] the disc studies forecast well the turbine's performance and wake in steady and low turbulent flows. However, the same cannot be stated in presence of waves, since only few have considered the turbine's interactions with wave-induced currents. The superposition of waves on a current field modify the turbulent behaviour of the environment under which the turbine must operate and in turn the turbine performance is different from the current alone case. In fact, Kemp and Simons, conducted laboratory experiments on current flows with [37] and against [38] wave direction. Their researches pointed out that: the unidirectional turbulent boundary layer is reduced in thickness by the superposition of waves propagating and flow reversal was experienced near the bed. Moreover, the presence of the waves, also directly interacts with the turbine thus directly contributing to the modification of its dynamical behaviour with respect to the currents only case. For tidal stream turbine, the effect of the wave on the stream flow have been the subject to intense debate among researchers. Currently, the majority of laboratory studies assume the surface waves and current are aligned, although realistic waves can propagate at different angles (likely at 90 degrees) due to wave refraction on the coast [21]. Therefore, both preliminary computational and experimental findings are subject to limitations. General observations in waves include: change of the wing vortex [15] and wake development [23]; reduction of the available power output as a function of the wave height [39]; enhancement of the deviations of the axial flow [23] and performance [19]; and retention of the steady thrust, power, and downstream flow features, in a quasi-steady sense [40]. Table 1 summarizes the most important details of previous laboratory experiments of tidal stream turbine operated in wave–current flows. In recent years,

a few studies, in particular, have focused on the wake features to provide reliable estimates of the flow's perturbation and interactions with other next-inline turbines. For regular waves, it penetrated the water depth by approximately half of its wavelength. The wave-induced wake depicts different patterns, depending on its distance from the rotor, into near and far regions, as is the case when considering current alone. Near region depicts non-symmetry and large alterations due to the wing-tip vortices [41], blockage of supporting structure [42], the counter rotating nacelle wake [43] and surface waves actions [23]. In the far field, at a downstream distance from the turbine greater than 5 rotor diameters (D), the wake retains a Gaussian lateral expansion, as observed without the waves. According to the existing research, the upstream ambient turbulence plays a major role in the behaviour of a single tidal stream turbine [44] and the array [45]. The turbulence intensity deeply affects the shape of tidal turbine wake. Mainly the wave frequency but also its amplitude even if in a lower extent, are also shown to affect the correlation of the far downstream fluctuations, measured by the time integral scale [23]. However, very few studies have been done to experimentally visualize the turbulent wakes in presence of wave. Performing an experimental study able to deliver a detailed visualization of the operating, complex flow and its properties is of fundamental importance in support of the enhancement of turbine design models and may offers other perspectives for treating the complex turbine dynamics. In turbulence, a common metric to determine the flow shear layers structure is through the level of its anisotropy. Tedds et al. [46] states the turbine near wake region in turbulent flow is anisotropic, contrary to what most turbulent models assume; however, as of today, it is unknown whether this finding applies in waves, and if so, to what extent and which factors.

The objective of this paper is to fill the gap in the literature by experimentally visualizing the internal effects of waves and turbulent in the wake of a tidal stream turbine. To achieve this, it is critical to quantify the mean wake and turbulence characteristic, in terms of the turbine power and wave characteristics, such as wave energy and its elevation. Contours of velocity deficit and turbulence intensities and the wake anisotropy are given for different streamwise positions. By understanding the wake nature in waves, it will help modellers to

(a) Schematic of the flume on the $x - z$ plane

(b) The turbine from upstream view

Fig. 1. Schematic and photo of the flume.

obtain correct predictions of tidal stream turbines in arrays and may contribute to the acceleration of tidal industrial undertakings.

This paper contains four sections:

- Section 1 introduces the background, research progress and existing problems;
- Section 2 explains the details of the test arrangement, turbine scale-model characteristics, and measurements of the undisturbed current and wave conditions;
- Section 3 assesses the wave-induced wake features: tidal performance, mean wake structure, wake swirl and turbulence characteristics;
- Finally, Section 4 describes our discussion and prospects for future.

2. Methodology

2.1. Experimental setup

The experiments were conducted in the flume of Shandong Jiaotong University in both current-only and wave-current flow. The flume is 57 m long, 1.2 m wide, 1.5 m deep, with a 6 m damping slope of 1 : 3 composed of gravel and cobblestones (see Fig. 1(a)). Water is pumped at far upstream, where porous plates were used to dissipate the large scale eddies and straighten the incident flows. A piston-type wave paddle is utilized to generate linear waves along the current direction.

The scale-model tidal turbine was deployed at the mid-depth of the water volume. The origin located at the rotor's centre. Longitudinal, transverse and vertical directions are defined as x , y and z (In Fig. 1(b)). Capital letters $X = x/D$, $Y = y/D$ and $Z = z/D$ are used to represent the dimensionless Cartesian coordinate system. A traverse-moving device was installed above the flume with increments of 1 mm. Length, width and depth of the flume test section is 4.4, 1.5 and 0.6 m, respectively. Inside this part of the flume, the flow field was measured by using an Acoustic Doppler velocimeter (ADV). Substantial amount of velocity points was measured by profiling, vertically and horizontally, a total of 18 vertical sections (yOz) located upstream (up to $-4D$) and downstream (up to $14D$) the rotor position. In each section, 25

points along the transversal and horizontal direction at the rotor centre level (from $-1.2D$ to $1.2D$) and 17 points along the vertical direction (from $-0.9D$ to $0.1D$) were measured. Distance between adjacent measurement points was $0.1D$. The velocity field in the same part of the flume was also monitored in absence of the rotor model to collected the necessary information for the comparative study. Fig. 2(b) depicts the position of the vertical yOz sections on which the velocities were measured. In this case the distance between sections was $2D$ and in each section 6 extra points near the flume bed were sampled with $Z < -0.9$.

2.2. Measurement techniques

In order to study the influence of wave following current on the turbine wake, measurements of wave motions, flow velocities, rotor torque and rotation were conducted. The sensors and measurement devices are shown in Fig. 4(a). As described in Fig. 1(a), wave gauges were situated at $10D$, $20D$ up and $20D$ downstream. Four-beam down (for horizontal samples) and side (for vertical samples) looking Vectrino+ were employed to record the time-varying velocity, with a range of 0 to 3.0 m/s. The sample rate of the velocity was 200 Hz and the sample volume height was 5.5 mm. The record period of velocity data at each point was 180 s which is long enough to eliminate the uncertainty on the time-averaged velocities.

To quantify the signal quality, the signal-noise ratio (SNR) and correlation coefficient (COR) of most samples ($\geq 90\%$) was determined and chosen to be greater than 15 dB and 80%, respectively. According to the postprocessing technique from Martín Romagnoli et al. [47], in terms of RECV (relative error contribution on raw variance), the uncertainty of the raw velocity data is less than 7% with the 95% confidence intervals. A typical 180 s sample is illustrated in Fig. 3 with the poorest quality behind the rotor centre. Velocity Signal Analyser (MAJVSA) was used to filter the velocity data to improve results. SNR and correlation were used as criterion for the pre-filtering technique, and the modified phase-space thresholding method was used for the despiking signal procedure. Similarity of results is assumed only if $1 < C_1 < 2$ and $1.25 < C_2 < 1.45$ [48], where C_1 and C_2 are the filtering

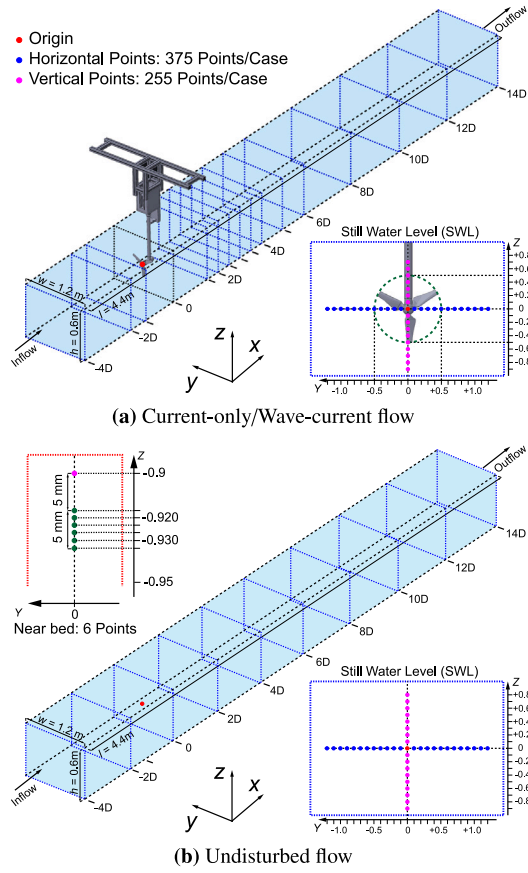
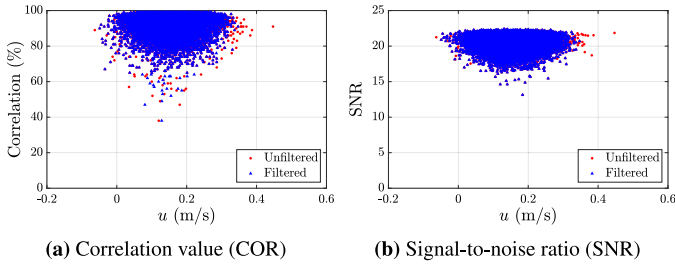


Fig. 2. Sample sections and positions in the water volume.

Fig. 3. ADV correlation (COR) and signal-to-noise ratio (SNR) of the sample with worst quality at $X = 1.5$, $Y = Z = 0$ in current-only flow.

parameters describing the mPST-SH auto-safe level and auto-exclude level, respectively.

Rotor torque and angular displacement were measured using a 0.2 N m T21WN torque transducer from HBM (Refer to Ref. [49]). The strain gauge technology-based transducer measures a nominal torque up to 0.2 N m, and the 360 PPR code-wheel provides the position, with a resolution of $\pi/180$. Angular speed was calculated by the differentiation of the angular displacement, with a full-scale range up to 20000 rpm. The full bridge strain gauges were applied to measure the thrust on the turbine. However, it is difficult to calibration the force with the strain gauges therefore the thrust in Fig. 8(b) is obtain using numerical investigation (Blade Element Method) instead of using the experimental strain data.

2.3. Model turbine

A three-bladed tidal-stream turbine was developed to extract the axial momentum of the tides. Both the support structure and blades

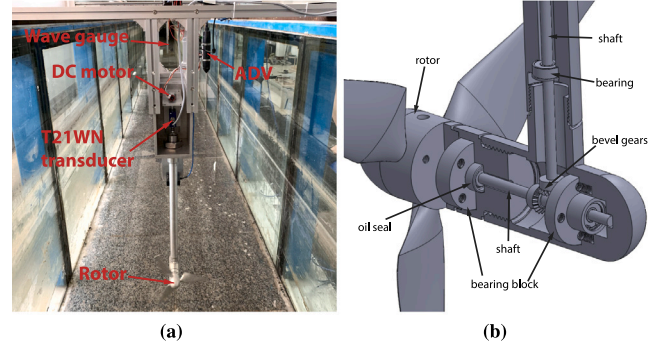


Fig. 4. (a) Photo of measuring device; (b) Transmission schematic.

Table 2

Radial variation of chord length and twist. $R = D/2$.

r/R	r (mm)	c/R	θ (deg)	t/c (%)
0.167	30	0.1	13.50	100
0.2	30	0.155	13.12	80
0.3	45	0.321	11.90	21
0.4	60	0.297	10.17	19
0.5	75	0.274	8.44	16
0.6	90	0.250	6.70	16
0.7	105	0.227	4.97	16
0.8	120	0.203	3.24	16
0.9	135	0.180	1.50	16
1.0	150	0.156	-0.23	16

were made of 6061-T4 aluminium alloy, by using a 6-axis CNC milling machine. Laboratory experiments on the tested model turbine can be considered representative, if scale 1 : 50, to an ideal tidal stream turbine prototype rated at 0.6 MW and operating at 2.8 m/s. The model was positioned with a 0.3 m immersion water depth, it has a rotor diameter $D = 0.3$ m, with nacelle's diameter and length of 0.05 m and 0.17 m, respectively.

The mean velocity of incoming flow was set at $U_0 = 0.4$ m/s, and the Flume Froude number is $Fr = U_0/\sqrt{gh} = 0.165$. Reynolds number at the blade tip is $Re = U_0 D/\nu = 1.2 \times 10^4$, where $\nu = 1.006 \times 10^{-6}$ m²/s is kinematic viscosity of water. The blades utilize NREL S822/S823 hydrofoil profiles, with a radial variation of twist angle (θ) and chord length (c) as indicated in Table 2. The main characteristics of the rotor blades were selected to attain similar peak efficiency to that of the full size turbine.

The transmission system is illustrated in Fig. 4(b). The turbine rotor was mounted on a 6 mm shaft, connected to a pair of 90 degree case-hardened bevel gears. The nacelle was installed on an upright tower of 36 mm diameter, located at 0.34D downstream. The control system consists of a 12 V DC motor with hall encoder and an Arduino Uno micro-controller. The rotation speed was controlled by closed-loop PI strategy.

2.4. Ambient current with and without waves

The turbine model was tested in two conditions: (i) the ambient current-only condition and (ii) the waves-following current conditions. Features of the generated ambient current-only and in presence of waves are presented in this paragraph to provide evidence of the specific tested conditions settled in the present work thus supporting a better understanding of results presented and discussed in the following paragraphs.

In order to profile the distribution of undisturbed ambient flow, initial experiments were conducted in the flume without turbine installed. To quantify the effect of bed shear layer, six extra points are sampled near the flume bed. The properties of the vertical profiles through the origin is illustrated in Fig. 5. To characterize the distribution of

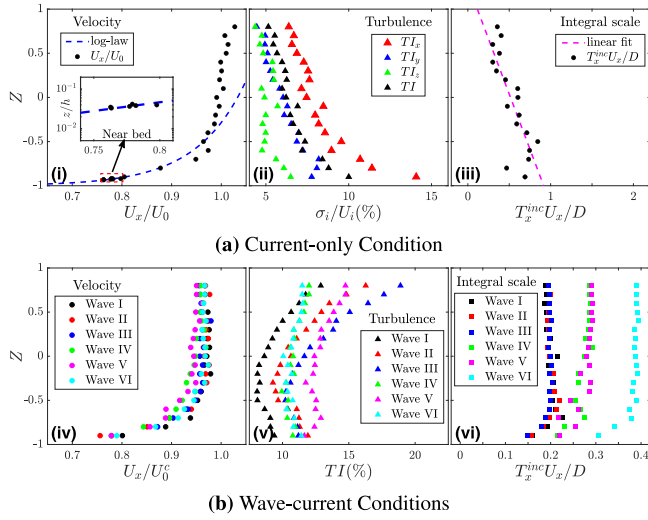


Fig. 5. Vertical flow properties on the $X, Y = 0$ profile without the turbine installed: (i)/(iv) Normalized axial velocity (U_x/U_0) and the near bed region; (ii)/(v) Turbulence intensities (σ_i/U_i); (iii)/(vi) Normalized longitudinal integral scale ($T_x^{inc} U_0/D$).

streamwise velocity, both the log and power law are applied in the samples near the flume bed ($Z < -0.9$).

$$\frac{U_x(z_0)}{U^*} = \frac{1}{\kappa} \ln \left(\frac{z_0 U^*}{\nu} \right) + 5.0 \quad (1)$$

Eq. (1) defines the log-law profile, where $\kappa = 0.41$ is the von Kármán constant and $U^* = 0.0161$ m/s denotes the estimation of friction velocity, which can be computed using a least-squares fitting with the longitudinal velocity (U_x) and bed distances (z_0) in the near-bed region.

Fig. 5(i) indicates the velocity profile along the vertical direction at $X, Y = 0$, whilst the sub-figure depicts six near bed sample points in detail. Clearly, the log-law method converges with the velocity distribution in $Z < -0.9$ but starts to diverge upwards; it fits well for $Z \leq -0.5$. From the comparison of sub-figure (i) and (iv), the vertical profile gets shifted parallel to the vertical axis. This also means that the reduction of mean streamwise velocity happened on the vertical profile, which is consistent with the result by Kemp et al. [37] and Singh et al. [50]. The turbulence intensities are evaluated as $TI_i = \sigma_i/U_i$, where σ_i is the standard deviation, U_i is the averaged velocity and the suffix $i = x, y, z$ means the velocity components. The water-depth averaged turbulence intensity is 6.2% at the rotor centre location which represents the daily variation of tidal flow velocity at the potential site. The three-dimensional turbulence intensity is evaluated as follows:

$$TI = \sqrt{\frac{1}{3} \left(\frac{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}{U_x^2 + U_y^2 + U_z^2} \right)} \quad (2)$$

As seen in Fig. 5(v), under the interaction of wave and current, the turbulence intensity shows a C-shaped distribution along the vertical profile. The turbulence increases with shallower waves on the upper half profile but reduces with deeper waves near the flume bed.

The longitudinal integral scale of the turbulence is described in Eq. (3), where τ is time lag and r_τ is the auto-correlation function. The integral time scale is determined up to small time lag, $\tau = 0.005$ s. Wave conditions present integral length scales between 0.3 to 0.8 times the rotor radius. The relative size of the integral length scale appears to be linked to power, thrust, and wake development of turbines. In the Ref. [34], a large length scale has been associated with greater wake recovery due to greater interactions between the overall wake and surrounding free-stream velocity. Contrary to expectations, the effect of integral scale size on wake recovery appears to be unclear,

Table 3

Wave conditions.							
Wave	Period	Height		Length		Steepness	Relative depth
		(alone)	(current)	(alone)	(current)		
	T (s)	H_0 (cm)	H (cm)	L_0 (m)	L (m)	H/L (%)	h/L
I	1.0	5.37	5.03	1.54	2.23	2.25	0.27
II	1.0	7.50	6.80	1.54	2.24	3.04	0.27
III	1.0	10.12	8.59	1.54	2.23	3.84	0.27
IV	1.5	5.24	4.99	2.99	3.83	1.30	0.16
V	1.5	7.51	6.83	3.00	3.83	1.79	0.16
VI	2.0	4.76	4.55	4.37	5.32	0.86	0.11

meaning preliminary current-alone results may not be generable to wave-induced conditions.

$$T_x = \int_0^\infty r_\tau d\tau, \quad \text{with} \quad r_\tau = E[u'_x(t)u'_x(t-\tau)]/\sigma_x^2 \quad (3)$$

As observed in Fig. 5(b), the turbulent intensities decrease exponentially with bed height. The integral scale follows (approximately) an inverse linear function with the bed height. $T_x^{inc} \approx 0.45$ is obtained at the turbine hub height.

2.5. Wave conditions

Linear or modified linear wave theory are widely used to investigate the wake characteristic of tidal stream [51]. They assume that the free surface profile is symmetric about the mean water level with single frequency $f = 1/T$. The modified linear wave theory considers the actual free surface elevation to compute wave kinematics (by Hansen (1988) [52] and Faltinsen (1990) [53]). Due to the turbulence generated by tidal current, it is difficult to apply these assumption about wave kinematics in the wave-current flow. In our research, linear wave theory, also known as Airy, is applied to predict the wave length for given water depth, wave period and current velocity, as measured in the experiments. For the wave-alone conditions, the dispersion equation is utilized as:

$$\omega_a^2 = gk_0 \tanh(k_0 h) \quad (4)$$

where $k_0 = 2\pi/L_0$ and ω_a is wave number and absolute angular frequency of waves for wave-alone conditions. For the wave propagating along the same direction of the turbulent flow, it experiences Doppler effect. The dispersion relationship becomes:

$$(\omega_a - k_w U_0)^2 = gk_w \tanh(k_w h) \quad (5)$$

where $k_w = 2\pi/L$ is the absolute wave number in wave-current flow. According to this equation, a wave propagating with the current leads to an increased wave length and a more gradual wave [54].

Table 3 illustrates the main parameter for the initial experiment. T is the time period for an absolute observer; H_0 , H and L_0 , L is wave height and wavelength in the absolute frame of reference for wave-alone and wave-current cases, respectively. Ursell number ($U_r = HL^2/h^3$) is a normalized parameter to evaluate the linearity of waves, where a maximum $U_r \approx 4.04 \ll 32\pi^2/3$ indicates the suitability of the theory. The comparison between wave-alone and wave-current conditions indicates a significant change in wave height and waveform. The time histories of normalized wave elevation are illustrated in Fig. 6. The sinusoidal behaviour of the wave is altered by the current, resulting in small harmonic and non-linear components. Fig. 7 shows the time-average velocities along the vertical in wave-current region and the related minimum and maximum wave-induced velocities on the same point along the vertical (as obtained by a frequency domain analysis of the velocity time series); as expected, the amplitude of this wave-induced velocities oscillation decreases through the water column and the decrement rate is greater for the shorter waves than for the longer

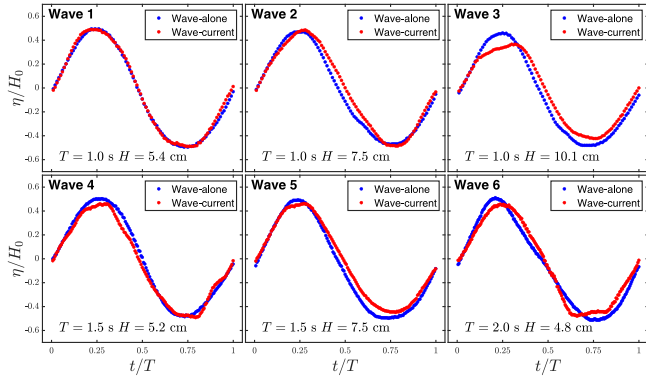


Fig. 6. Time histories of normalized wave elevation (η/H_0) under wave-alone (blue) and wave-current (red) conditions.

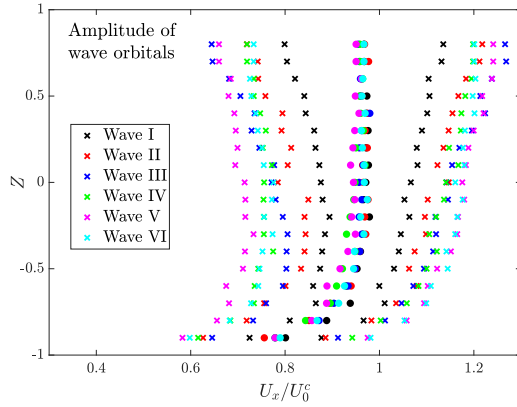


Fig. 7. Velocities of wave orbital (Average (o) and amplitude (x) in wave-current flow).

waves. It highlights that longer waves cause a deeper penetration throughout the water column of their effects in the tidal current field in turn affecting the rotor wake to a greater extent.

According to linear wave theory, the mean wave energy density (E_w) can be expressed as: $E_w = \rho g m_0$ [55], where m_0 is the variation of wave elevation. The transport velocity of wave energy is equal to the group velocity (C_{group}) of wave. As a result, the flux of wave energy can be defined as: $P_w = E_w C_{group}$ [56]. The phase velocity (C_{phase}) of the linear waves is:

$$C_{phase} = \frac{L}{T} = \sqrt{\frac{g}{k_w} \tanh(k_w h)} \quad (6)$$

Due to frequency dispersion, the group velocity represents the moving speed of wave pattern groups and for deep water wave conditions, $C_{group} = 1/2 C_{phase}$, which means that the phase celerity is twice the group celerity [57]. The ratio between the group and phase velocity is:

$$\frac{C_{group}}{C_{phase}} = \frac{1}{2} \left(1 + \frac{2k_w h}{\sinh(2k_w h)} \right) \quad (7)$$

Table 4 shows the wave energy density and flux in wave-current flow. According to this table, due to the longest wave period, Wave VI has the highest group velocity but the lowest energy density due to the lowest wave height.

3. Result and discussion

3.1. Turbine performance

In order to describe more comprehensively the features of the tested turbine model, in support of a better understanding of results described

Table 4

Wave energy density and flux in wave-current flow.

Wave	Period T (s)	Phase velocity C_{phase} (m/s)	Group velocity C_{group} (m/s)	Energy density E_w (J/m ²)	Energy flux P_w (W/m)
I	1.0	1.805	1.111	9.46	10.52
II	1.0	1.805	1.112	30.82	34.15
III	1.0	1.805	1.111	80.62	89.60
IV	1.5	2.125	1.659	8.17	15.21
V	1.5	2.124	1.658	31.05	52.13
VI	2.0	2.251	1.947	6.89	13.42

in the following paragraphs of this study, the turbine performance is characterized through parameters including: (i) tip-speed ratio, (ii) blockage ratio, (iii) thrust and (iv) power coefficient.

Tip-speed ratio or TSR is the ratio between the tangential velocity at the rotor tip to the mean velocity of incoming flow:

$$TSR = \frac{U_T}{U_0} = \frac{\omega_r R}{U_0} \quad (8)$$

where U_T and ω_r is the tip-tangential and angular velocity, respectively.

In our research, rotor of the turbine produced a flume sectional blockage ratio expressed as:

$$\alpha = A/(wh) = 9.8\% \quad (9)$$

where $A = \pi R^2$ is the swept area of the rotor blade, w and h are the width and mean height of the water field respectively. The thrust coefficient is defined as in Eq. (10)

$$C_t = \frac{F}{0.5 \rho A U_0^2} \quad (10)$$

where F is the thrust on the turbine and ρ is the water density. The power coefficient is expressed as:

$$C_p = \frac{M \omega_r}{0.5 \rho A U_0^3} \quad (11)$$

where M is the shaft torque measured from the transducer. As indicated in Eq. (11), power coefficient is defined as the ratio of the power extracted by the turbine and available power from the incident flow. For an unbounded steady flow, the maximum ideal power coefficient is $C_p = 16/27 \approx 0.593$ (see Betz [58] and Joukowsky [59]), although this is altered in a constrained [60] or wave-induced flow [21], as typical of tidal stream sites. The time series of instantaneous C_p and time averaged values: $\overline{C_p}$, $\overline{C_t}$ vs. TSR curve are represented in Fig. 8. As seen in sub-figure (b), the maximum $C_p = 0.33$ occurs for the TSR = 3.9. The dimensionless C_p and TSR are corrected with α using the modified Glauert's equations, summarized by Bahaj et al. [27]. In our study, the correction is 7.28% for C_p and 2.37% for TSR, by assuming a thrust coefficient $C_t = 0.8$.

3.2. Mean wake characteristic

Fig. 9 depicts contour maps of the mean velocity deficit (defined as: $\Delta U_x/U_0 = 1 - U_x/U_0$) on mid-depth (xOy) and centre-plane (xOz). Part of the flow bypasses the turbine and accelerates in order to compensate for the velocity reduction in the wake and thus conserve the mass flow rate; an increment of velocity is observed near the flume walls (Fig. 9(a)). This portion does not extend more than $8D$ downstream, among all the tested cases. In any case, downstream of the rotor, a wake where significant reduction of axial velocity is clearly noticeable for all tested conditions, is present. The shape of this wake is not remarkably affected by the superposition of waves.

A second bypass flow region is also noticeable below the model (Fig. 9(b)) where, once again, increment of local velocities appears. It is caused by a flow confinement effect due to the presence of flume bottom. However, this portion of velocity field with accelerated flow

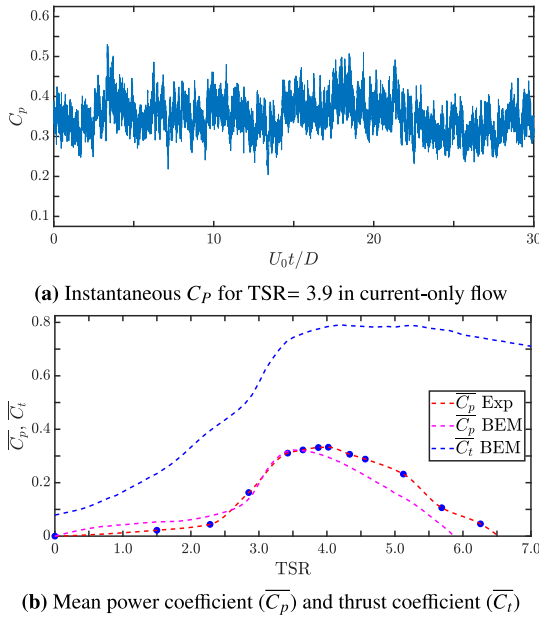
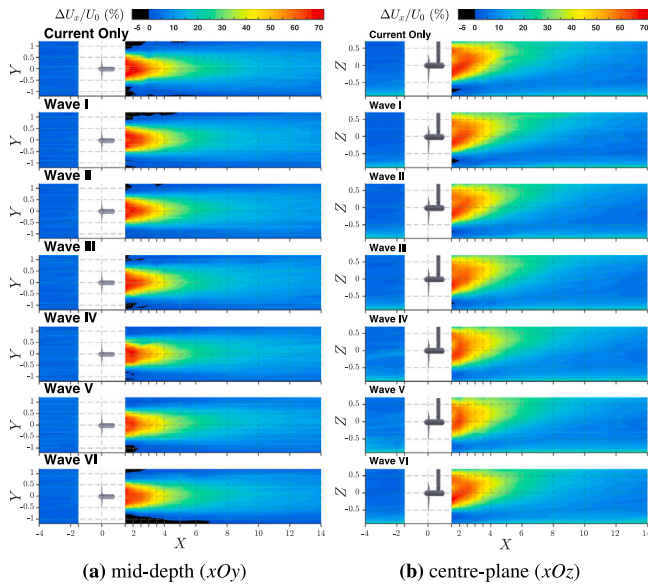


Fig. 8. Turbine performance in the current flow.

Fig. 9. Contours of longitudinal velocity deficit ($\Delta U_x/U_0$) across xOy and xOz planes.

disappears in case of the longer tested wave periods. It may be caused by different wave–current interactions taking place in the bed shear layer as function of wave period.

Fig. 10 depicts the longitudinal, transverse and vertical variation of mean axial velocity deficit. Sub-figure (a) indicates that the maximum deficit in longitudinal direction was measured at $2D$ distance downstream instead of at the closest point (i.e. $1.5D$).

Looking at the velocity profiles along the transverse direction at mid-depth, as plotted in Fig. 10(b), it is noticeable that the local velocity field with the higher deficit is measured at $1.5D$ downstream of the rotor where the maximum deficit is about 70% (in fact, the absolute maximum is 70.2% and it happens in the case of current-only, not shown in Fig. 10). The transverse profiles of the mean wake are almost symmetric and follow a double peak profile at $1.5D$ with peaks at $|Y| = 0.3$ (same as Ref. [29]). Then, after $4D$ section, they convert to a single Gaussian distribution with the height of peak decreasing

streamwisely, until nearly reaching the upstream profile at $14D$. The wakes from different generators do not tend to precisely the same self-similar state [61]. However, due to the interaction of wave and ambient turbulence, it is difficult to separate the wave-induced fluctuation from measurements. Beyond $10D$ downstream, the vertical flow almost recovers, the largest deficit occurs at $X = 1.5$, $Z = -0.2$ position, with a value of 69%.

After passing the rotor ($1.5D$), the vertical profile follows a double sigmoid function (Fig. 10(c)), with the upper plateau ($Z = 0.4$) altered by the stanchion and surface effects (similar as Ref. [62]), the middle plateau ($Z = 0.2$), by the wake, and the lower plateau ($Z = -0.2$), by the bed shear layer. Moving in the downstream direction, the profile becomes a single sigmoid curve (upper profile disappears), with plateaus slowly increasing, until reaching the exponential profile. The vertical profile close to the flume bottom is slightly influenced by the bed shear layer over range $Z \leq -0.5$, and the time-averaged deficit is almost a constant of about 15%. These profiles reveal a high similarity of average velocity deficits with or without wave-induced turbulence (same as Ref. [13] and our previous study [23]).

The mean wake structure (streamline) in the combined flow can be determined via the thickness of the shear layer [63]. This is defined across the lateral profile [64] using Eq. (12), where the radius R_δ denotes the position of the maximum observed velocity gradient.

$$\delta = U_0 \left(\frac{dU_x}{dr} \bigg|_{r=R_\delta} \right)^{-1} \quad (12)$$

In Fig. 11, the black curves represent the best-fit (least-squares method) of a Fourier approach for the multi-case averaged velocity, using interpolation of the experimental data, whilst Fig. 11 pinpoints that the thickness and radius are asymmetric about the rotor centreline. At the first section measured downstream, δ is approximately $0.57D$ and $0.47D$ for $Y+$ and $Y-$, respectively. Over $X \leq 3$ downstream, shear layer radius decreases and reaches to the rotor radius R at $X = 2.5$. The boundaries of the shear layer interact slightly and offset the wake centre at around $2.9D$, due to the increasing rate of expansion before the $3D$ section.

In order to illustrate the evolution of integral time scale, the log-log distributions of T_x are represent in Fig. 12 along the bottom-tip ($Z = -0.5$), mid-depth ($Z = 0$) and top-tip ($Z = 0.5$) axis. Negligible changes of T_x are observed after a certain distance downstream. Note that, compared to the wake along rotor centre ($Z = 0$), a higher variation-rate of integral scale ($d(T_x)/d(x)$) and a longer diffusion range is exhibited along rotor tips ($Z = \pm 0.5$). This behaviour is also noted by Jin et al. [65] and Liu et al. [66] in the wake of wind-turbine.

3.3. Wake swirl

Similar to a propeller jet, the tidal turbine wake can be described as a swirl flow generated by the rotor operated in the water field with a free surface. In swirl flows, the conservation of angular momentum leads to the generation of free vortex flow, in which the tangential velocity (U_t) increases from the rotor tips and decays to zero at the rotor centre. To characterize the influence of vortex breakdown in the wave-induced flows, the strength of swirl is typically quantified by the swirl number (S_w) [67], defined in Eq. (13):

$$S_w = \frac{\int_0^R U_x U_t r^2 dr}{R \int_0^R U_x^2 r dr} \quad (13)$$

where U_x and U_t are mean axial and tangential velocities, R is the hydraulic radius, expressed as the radius of rotor. In our test, the swirl number is derived from the integration of mean axial (U_x) and tangential (U_t) velocities at the gauging points distributed along cruciform-shaped region across yOz plane (Fig. 2(a)).

Fig. 13 contours show the mean tangential velocity (U_t), highlighting the effect of swirl flow. The wake rotation is found to be counter-clockwise and opposite to the rotor rotation (also in Ref. [43]).

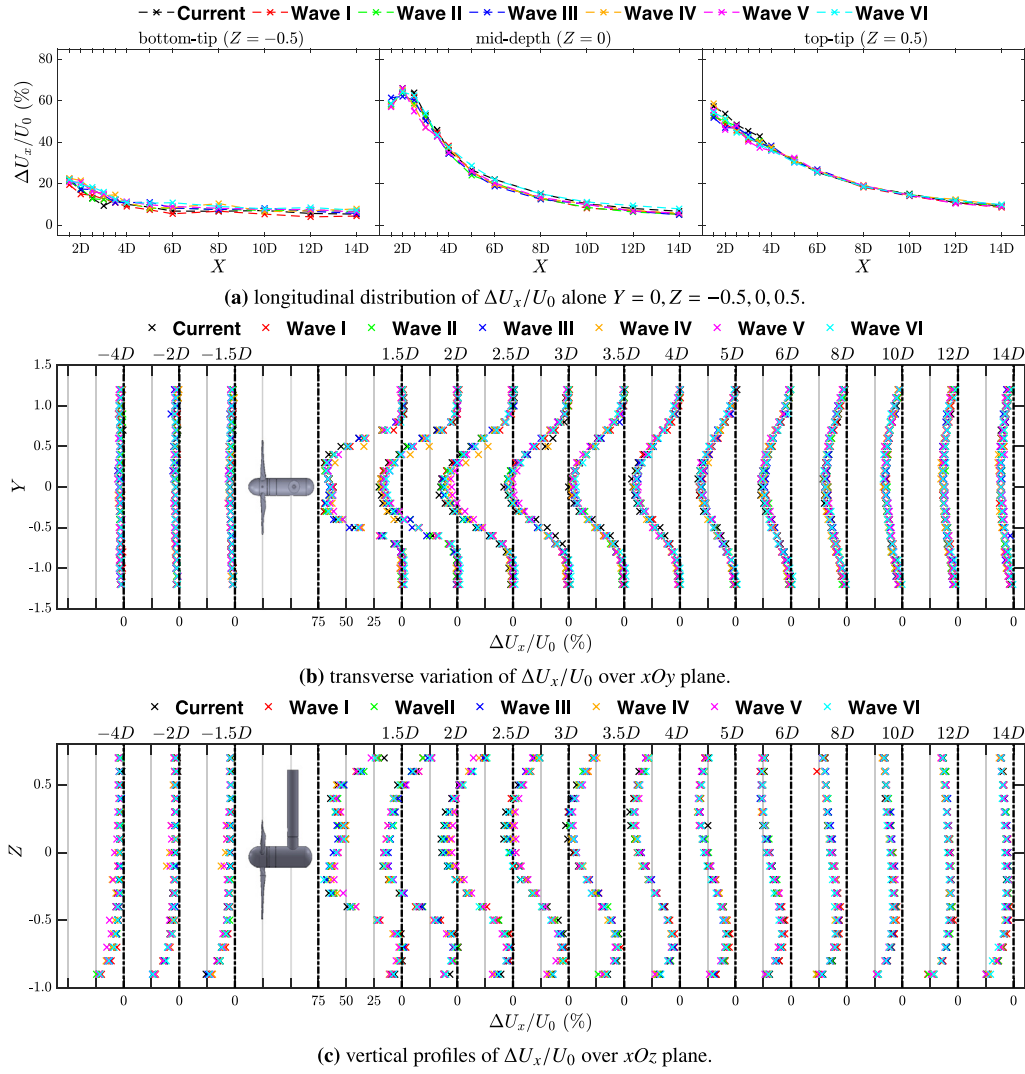
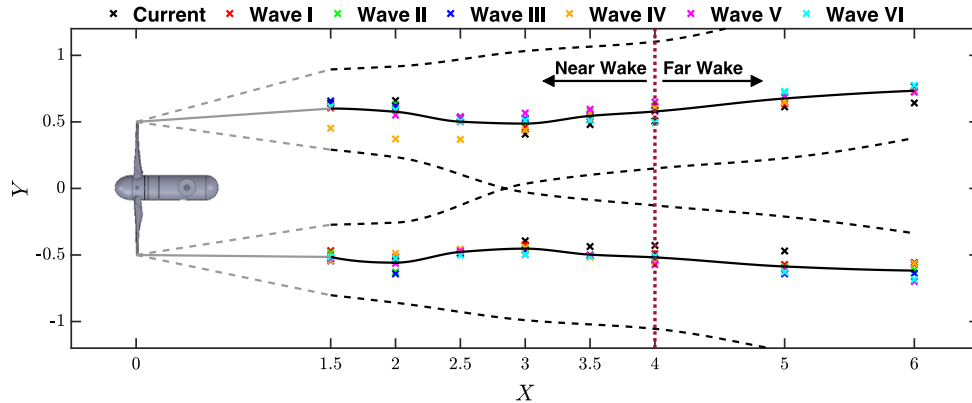
Fig. 10. Mean axial velocity deficit ($\Delta U_x/U_0$).Fig. 11. Multi-case averaged R_δ (black-curve), extents of the thickness δ (dashed curve) on xOy plane.

Fig. 13(a) shows that transverse tangential positive and negative velocity regions leaving the tips are asymmetrical with respect to the rotor centre. Clearly from this figure, the centre of the wake, with negative velocity, tilts upwards to the upper edge of the measurement field. In the current-only case, the negative part tends to diffuse and disappears in the near wake. On the contrary, in presence of waves,

the wave-induced local velocity field (i.e. at mid-depth) interact with the turbine wake and it leads to an extension of the negative velocity part far downstream.

Owing to the free surface effect, again, the asymmetry also occurs along the centre-plane. From another view (Fig. 13(b)), the tangential velocity is affected by the pile and diffuses upwardly, extending until

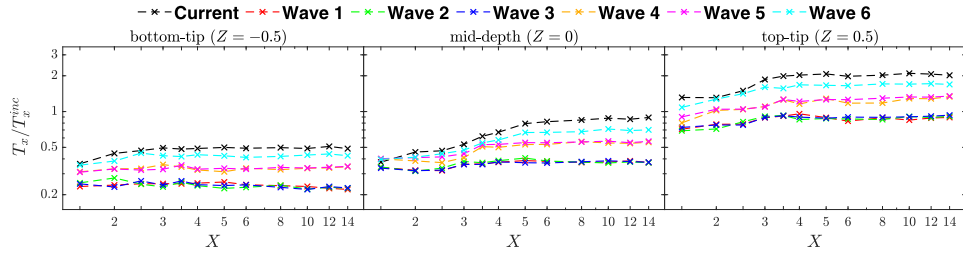


Fig. 12. Normalized integral time scale (T_x/T_x^{inc}) along different axis across xOz plane.

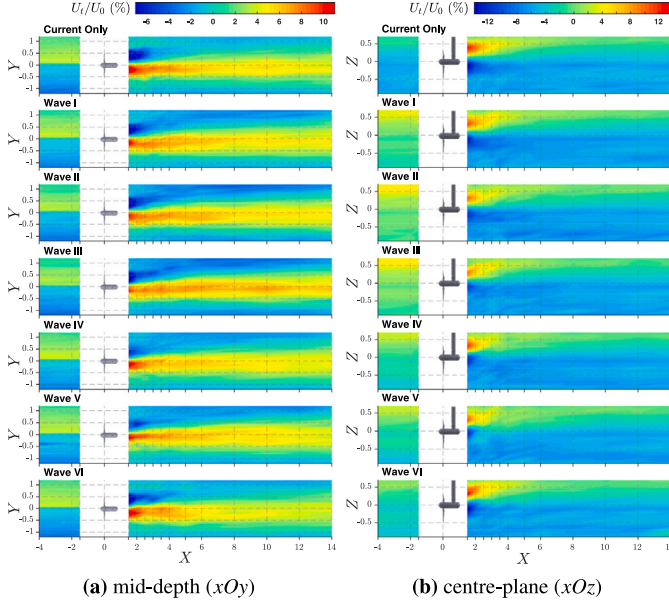


Fig. 13. Contours of the mean tangential velocities across xOy and xOz planes.

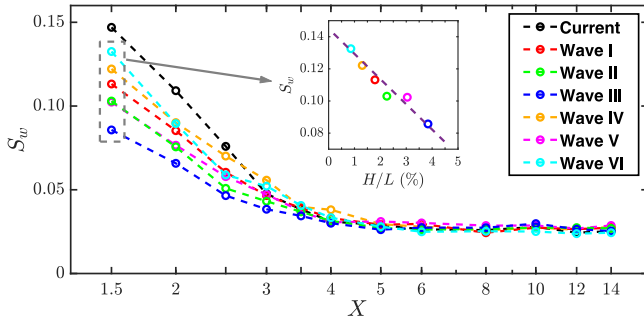


Fig. 14. Longitudinal distribution of Swirl Number (S_w) downstream of turbine (Semi-log-X).

the far wake; the effect with waves is minimal. However, the swirl propagates downwardly and rapidly disappears (even further with the waves).

The semi-log plot in Fig. 14 depicts the swirl number (S_w) calculated at different distances along the rotor centreline. The wake swirl is considered weak when $S_w \leq 0.2$ [68]. The presence of turbine rotor results in a swiftly drop of S_w within $X \leq 4$ [68] similar as a classic generator [67]. The swirl number curves in presence of waves, departs from the current-only curve and decreases longitudinally up to $4D$ where the swirl curves turn to be close to the current-only case. Then all level off at $S_w = 0.027$, same as Ref. [67] and [43].

Fig. 14 also compares the decay of wake swirl in different wave-current flows. The increase in wave height slows down the dissipation

of the vertical velocity in the wake but accelerates the development of the lateral velocities. The shorter and higher wave conditions of the steeper wave (Wave III) lead to the highest reduction of swirl number in the near wake field ($X \leq 4$). Moreover, it is depicted in the sub-figure that the lower the wave steepness the lower the swirl number reduction. The energy and flux are found to be the most critical factors affecting the wake swirl. Waves with more energy significantly hinder the axial flux of angular momentum which leads to the break up of large-scale vortices in swirl wake. The result suggests that the swirl number is negatively correlated with the wave energy density at $X \leq 4$ downstream.

3.4. Turbulence and its anisotropy

Fig. 15 illustrates the total turbulence intensities (Eq. (2)) in the wake of turbine with and without wave effects. According to this figure, the high turbulence regions are close to the position behind the rotor tips.

The horizontal distributions of TI at mid depth, are almost symmetrical with respect to the rotor centreline. Same as the location of maximum velocity gradient mentioned in Fig. 11, the maximum TI occurs behind the rotor-tips line and its value is around 23% for wave V condition. In the near-wake region, a low-turbulence core exist due to the blockage of nacelle. In presence of the wave-current region the turbulence intensities are higher than the current-only case across all the measuring domain. In particular, this enhancement of turbulence intensity values is higher in the region close to the free surface ($Z \geq 0.5$).

On the other hand, the turbulence intensity wake is asymmetrical on vertical plane (xOz plane). Similar to the wake deficit profiles, the centreline of wake turbulence tilts up towards free surface. The TI in the current-only case expands in a concave upward shape, with the focal point at the rotor centre and the curvature prolonging from the tips. In the presence of waves, TI in wake near-field region ($X \leq 4$) is increasing and the higher values are located close to the tips and the free surface. Wave cases IV and V exhibit an extra high TI area located downstream about $4D$ far the rotor.

Fig. 16 shows the longitudinal and lateral distributions of total intensity. In agreement with Ref. [13], the presence of waves significantly affect the turbulence intensity rather than the mean wake deficit.

Longitudinally (see Fig. 16(a)), the TI at the bottom-tip decreases exponentially from $TI = 16\%$ at $2D$ to $TI = 6\%$ at $14D$. At the mid-depth, the TI drops near the turbine but then jumps at $4D$, before decreasing slowly, thereafter. At the top-tip, the TI stays almost constant up to $4D$ but then decreases slowly. The waves TI profiles follow the current's, although higher values are highlighted; except at the top tip for $X > 4$, where the wave decreasing order modifies for wave II and V. The blockage effect of flume side-walls causes higher turbulence intensity relative to upstream sections.

Due to the presence of turbine nacelle and wave-induced effects, the maximum TI is observed at $1.5D$ downstream along top-tip axis, where its value is 19.6% (Fig. 16(b)). The highest increment of TI , due to the wave effects, on the horizontal plane at mid-depth is located in the shadow area just behind the turbine nacelle, there where the two shear

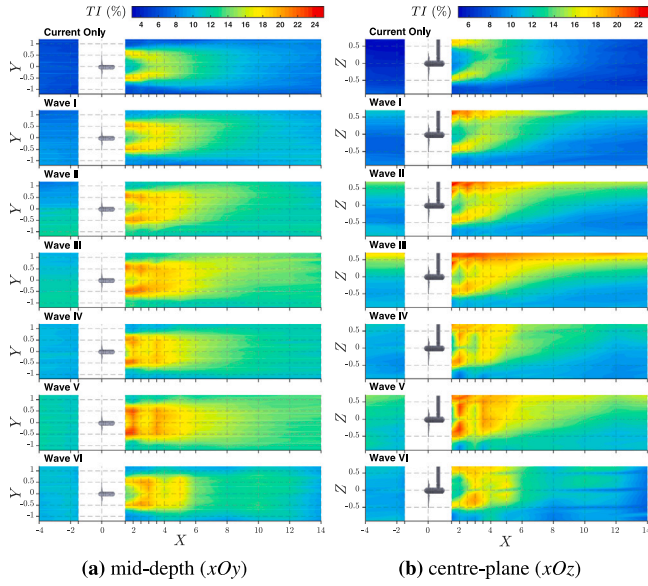


Fig. 15. Contours of total turbulence intensity (TI) across xOy and xOz planes.

layers arising from the blade-tips but do not extend further downstream and the turbulence intensities keep decreasing. Further downstream, the turbulence intensities keep decreasing. Over the range of $X \geq 5$, the total turbulence increases for increasing wave height and decreasing wave length so, as such, the wave steepness plays a major role.

The transverse profile of TI at mid-depth under waves is comparable with the current-only case (but shifted toward higher TI values) to the current-only case; The highest increment of TI is induced by wave V while the lowest increase is due to wave I. In this case, the increment of TI is not fully explained in terms of wave-steepness as it happens for the wake field close to the free surface.

The TI profile upstream of the rotor is almost flat, with a $TI \approx 5\%$ for the current, compared with TI of $\approx 12\%$ (Wave V) and TI of $\approx 8\%$ (Wave I). After passing the rotor, the TI is a bimodal distribution of

same variance, with peak ($Y = \pm 0.6$) heights decreasing longitudinally. At $12D$ section, the TI profiles are similar to the upstream profiles.

As declared in Ref. [46], most studies have modelled the turbulence wake of tidal stream turbine using the isotropic turbulence models. Thus it is impossible to represent the rate of return to isotropy and the turbulence anisotropy. Afgan et al. and McNaughton et al. suggest that although RANS models can also provide acceptable predictions of mean power and thrust [69], however, LES yields detailed behaviour for blade tip vortices and their interaction in the wake, neither of which are captured completely by the RANS models [70]. In general, the components of Reynold-stress anisotropy tensor can be expressed as: $b_{ij} = \langle u_i u_j \rangle / \langle u_k u_k \rangle - \delta_{ij}/3$; where the suffixes i, j, k represent the velocity components and δ_{ij} is the Kronecker delta. To simply described the anisotropy of turbulence wake, the state of anisotropy can be characterized as two independent invariants ξ and η , respectively (see Eqs. (14) and (15)). The eigenvalues of the tensor are λ_1, λ_2 and λ_3 .

$$\eta^2 = \frac{1}{6} b_{ij} b_{ji} = \frac{1}{3} (\lambda_1^2 + \lambda_1 \lambda_2 + \lambda_2^2) \quad (14)$$

$$\xi^3 = \frac{1}{6} b_{ij} b_{jk} b_{ki} = -\frac{1}{2} \lambda_1 \lambda_2 (\lambda_1 + \lambda_2) \quad (15)$$

According to Fig. 17, in terms of invariants, the black curves (also known as Lumley triangle even if the base is not straight) represent the special states of Reynold-stress anisotropy tensor η and ξ . For realizable turbulent flow, the Reynolds stress should corresponds to a specific point inside the Lumley triangle [71]. In this triangle, the origin corresponds to the isotropic turbulence, signifying that the velocity fluctuation does not depend on the direction ($\lambda_1 = \lambda_2 = \lambda_3 = 0$). The vertex on the right-top denotes a one-component turbulence, thus $\lambda_1 = 2/3, \lambda_2 = \lambda_3 = -1/3$. The two lines connected to the origin represent axis-symmetric turbulence: if $0 \leq \xi < \eta$, the shape of Reynold-stress ellipsoid is a prolate spheroid; when $-\eta < \xi \leq 0$, the shape of Reynold-stress ellipsoid is a oblate spheroid.

In order to observe the anisotropy of the turbine wake, six measurement points are used around the top ($0.4 \leq Z \leq 0.6$) and bottom ($-0.6 \leq Z \leq -0.4$). In the near-wake region ($X \leq 4$), owing to the large-scale wing-tips vortices, the anisotropy is slightly influenced by the tested wave period and it is more likely to be a prolate spheroid

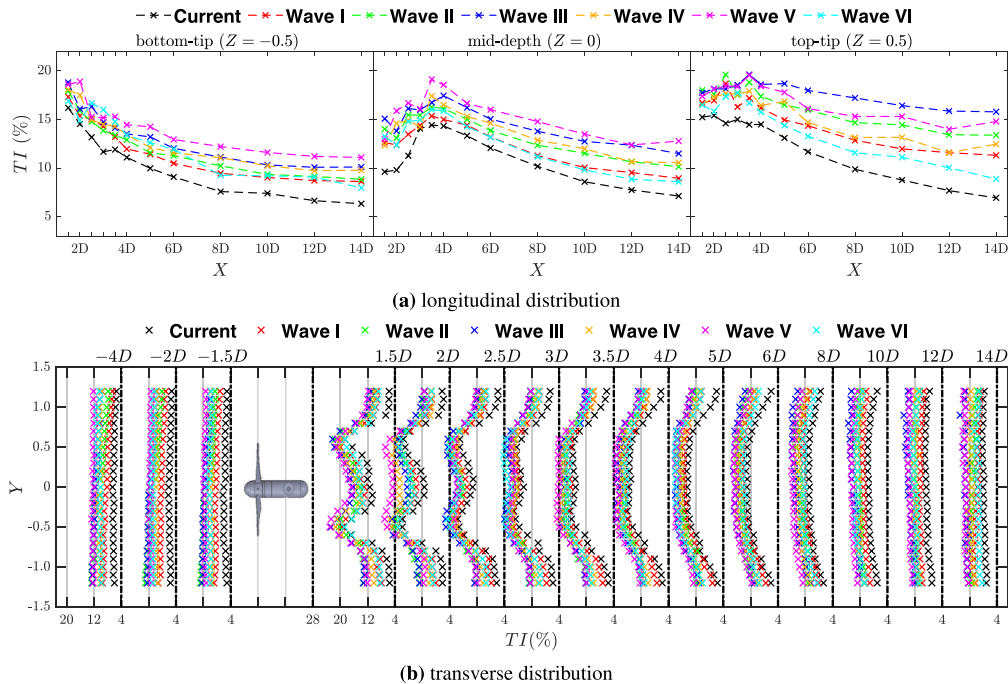


Fig. 16. Profiles of total turbulence intensity (TI) at hub height.

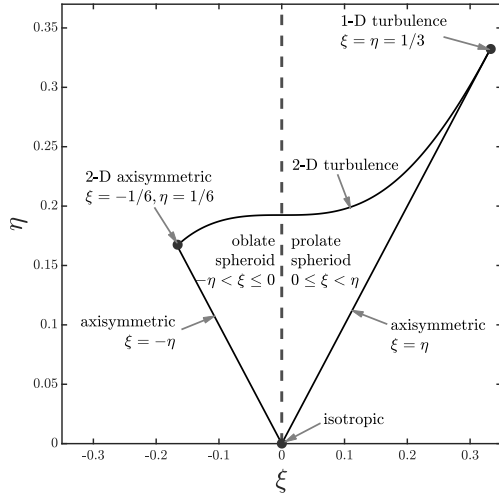


Fig. 17. The Lumley triangle (turbulent anisotropy map) of the invariants ξ and η .

shape (also called cigar shape [46]) turbulence. Within the near wake, the turbulent current expands axisymmetrically (prolate spheroid) and its anisotropy ($\eta \approx 0.1 - 0.2$) increases for the top of the tip but reduces for the bottom-tip streamwisely. In the presence of waves, the Reynold stresses move further toward the axisymmetric line but become more dispersed for the wave IV, V and VI than for the remaining cases. On the contrary, due to the wave-induced effect, wake anisotropy (η variant) increases for the bottom-tip and reduces for the top tip. The effect with downstream distance is not clear.

For $X \geq 5$, the interactions of waves and ambient flow have significant influence on the wake anisotropy. As seen in Fig. 18(b), it is more concentrated for the turbulence anisotropy as result of increasing wave energy density flux. In the far wake with current only, the shape of the turbulence is a mixture of more prolate than oblate spheroid and the mean anisotropy is $\eta \approx 0.13$. In Wave I, the flow displays a largely non-homogeneous turbulence (averaged $\eta \approx 0.14$), with a shape between the oblate and prolate spheroid. Compared to wave I, the wave II displays a more homogeneous state (prolate spheroid), although some closely oblate spheroids can be seen in the top tip. In the last waves, the turbulent state is highly homogeneous but the anisotropy is large, tending to a 1-component state (straight shape).

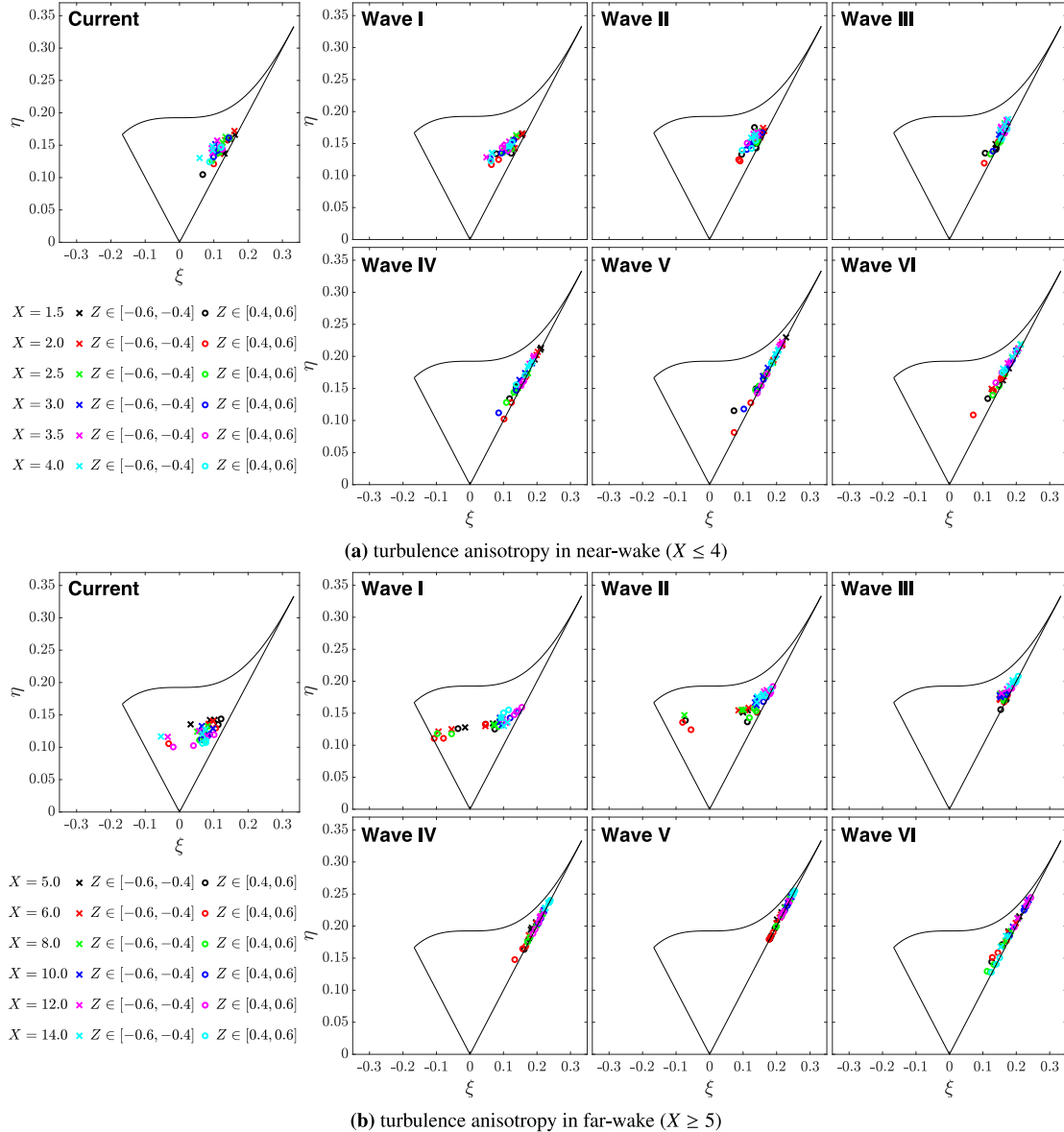


Fig. 18. Longitudinal variation turbulence anisotropy over $Z \in [-0.6, 0.4]$ and $[0.4, 0.6]$ in the Lumley triangle downstream of turbine.

4. Conclusions

The aim of our work is to broaden the knowledge of the turbine's wake under waves and current. To experimentally visualize the flow, various experiments were conducted in a scale model in a wave-current flume. Analysis of the mean flow deficit, wake swirl, TI , and anisotropy are presented focusing in the downstream near and far fields. The main results can be summarized as follows:

- The mean wake deficit is slightly influenced by the presence of waves. The horizontal velocity deficit profiles follow a double peak distribution near the rotor, and a single Gaussian distribution, afterwards. Meanwhile, due to the interactions of turbine supporting, water surface, and flume bottom, the vertical profiles follow a double sigmoid function in near wake field and a single sigmoid in the far wake field region.
- In general, the wake expansion is slightly asymmetric about the rotor centreline. The swirl number exhibits a decreasing trend moving downstream in the near field and it becomes almost constant in the far field. At $1.5D$ downstream of the rotor, the swirl number is drastically influenced by the waves. A clear reduction is noticeable, and it is well correlated to the wave-steepness.
- The presence of waves significantly affects the turbulence intensity rather than the mean wake deficit. Due to the shadow effect of the turbine nacelle, a low-turbulence core exists in the near field ($X \leq 4$) and the TI follows a bimodal distribution, that tends to a constant distribution moving downstream. In presence of waves, TI is higher than in the current-only case throughout all wake region. The vertical distribution of TI indicates higher values located between top-tip level and free surface.
- The turbulence anisotropy has been studied in terms of turbulent anisotropy maps. The turbulent flow exhibits a prolate spheroid shape in the near wake field, and a mixture of more prolate than oblate spheroid in the far wake region. The presence of waves leads to a non-isotropic turbulence regime where velocity fluctuations occurs mainly along the wave propagation direction. This result suggests that non-isotropic turbulence models should be the candidate models for numerical simulations when dealing with wake studies.

It is worth pointing out that the results of this study are related to certain laboratory Reynolds number and blocking ratio and so scale and laboratory effects have certainly affected the studied phenomena. In order to limit scale and laboratory effects, experiments with larger model (i.e. larger Reynolds number) tested on a wider flume (i.e. smaller blocking ratio) are needed to confirm general validity of these results.

CRedit authorship contribution statement

Yuquan Zhang: Methodology, Data curation. **Wei Zang:** Experiment, Data analysis, Writing - original draft. **Jinhai Zheng:** Supervision. **Lorenzo Cappietti:** Writing - resubmitted draft, Reviewing and editing. **Jisheng Zhang:** Validation. **Yuan Zheng:** Conceptualization. **E. Fernandez-Rodriguez:** Writing - revised draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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