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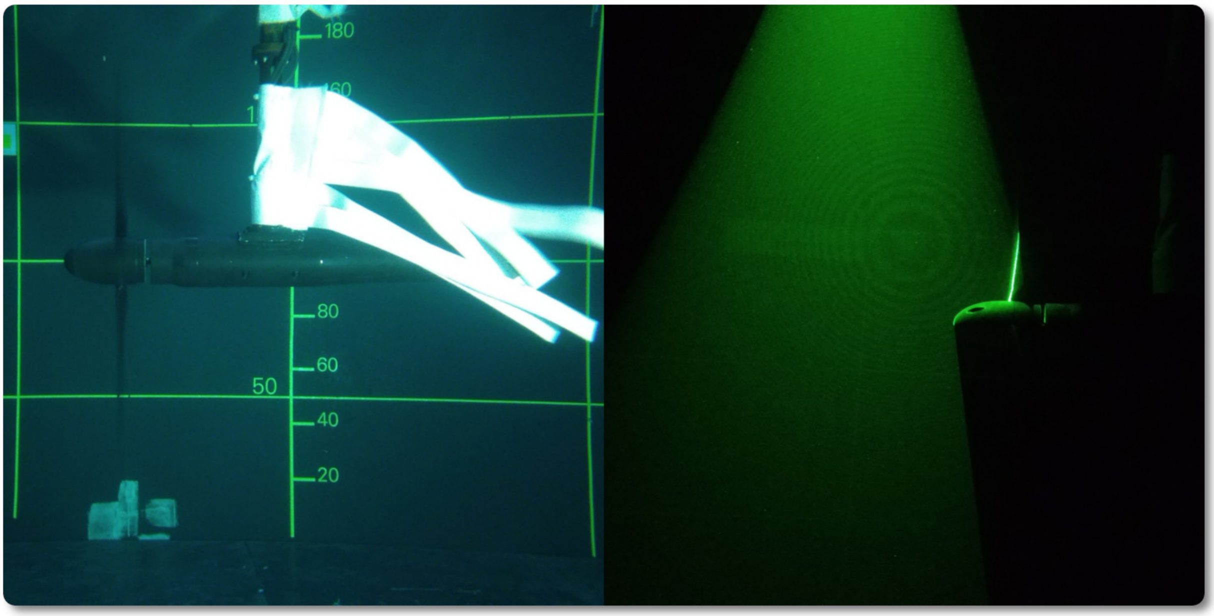
COMPARISON OF THREE DIFFERENT TURBINE DESIGNS IN UNSTEADY FLOW CONDITIONS

Experiment summary



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Résumé / Abstract :

This document presents the experimental tests carried out in the wave and current flume tank of IFREMER at Boulogne-sur-mer, France. The main objectives of these tests is to compare the performance measured on a model scale of a three-bladed horizontal axis tidal turbine when equipped with three different blade designs.

Mots clés / Key words :

horizontal axis tidal turbine, performance comparison, wave and current interactions, laser doppler velocity measurements, wave gauges

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Contents

Introduction

The purpose of the experiments is to compare how three different turbine designs perform in unsteady flow conditions: in turbulence and in surface waves (Gaurier et al. 2020b). An additional objective is to characterise the unsteady inflow conditions, and correlate them to the measured turbine loads.

The turbine performance is measured in steady and unsteady flow, through torque and thrust transducers. The inflow is characterised through 2-components and 3-components LDV systems and PIV measurements. The two LDV systems are used to take simultaneous 2-point measurements of the turbulent flow, at several locations in the turbine plane. This is done in an empty tank, i.e. when the turbine is not deployed. The purpose is to measure the spatial correlation of turbulent gusts in the turbine plane, by measuring at two locations simultaneously.

When the turbine is deployed, one velocity measurement point (using the 2-components LDV) is always acquired upstream of the turbine hub and in synchronization with the turbine parameters.

Time-resolved PIV recording at 15 Hz is used to measure the flow adjacent to the turbine when operating in turbulence. The PIV plane includes the upper half of the turbine diameter, i.e. the edge of the turbine nose is just visible on the bottom right side of the PIV plane. These PIV measurements are acquired in synchronization with the turbine parameters.

These LDV and PIV measurements enable the correlation and the coherence between the inflow characteristics and the turbine parameters to be processed, as previously performed in Gaurier et al. (2019) and Gaurier et al. (2020a)

1 Experimental facility

The tests take place in the wave and current flume tank of Ifremer at Boulogne-sur-mer, France. The experimental working section is 4 m wide by 2 m deep and 18 m length (figure 1). Two pumps generate a turbulent flow with a speed range between 0.1 to 2.2 m/s.

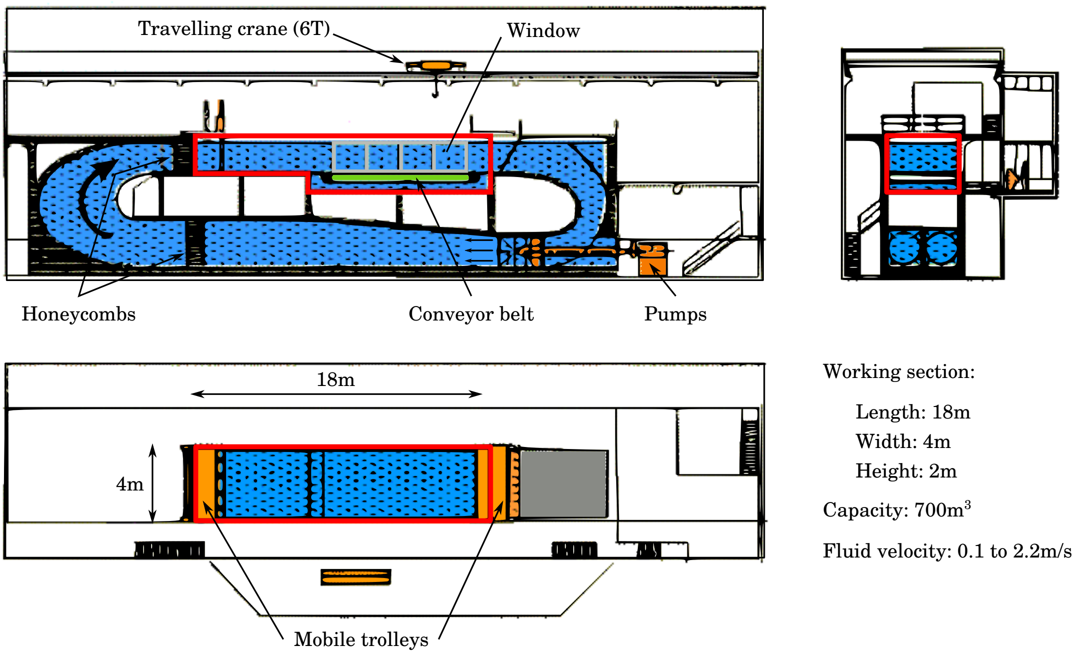

Figure 1 – Schematic of the wave and current flume tank

The turbulent intensity rate can be regulated by the use of flow straightener and grid. With both of them, the turbulent intensity is about $I_\infty \simeq 1.5\,\%$. When the grid and the flow straightener are removed, I_∞ reaches values of about 15 %. These turbulent values are constant along the test area, because it is self-sustaining by the two pumps generating the flow in the tank.

In addition to the flow velocity, waves can be superimposed to the current using a wavemaker (Gaurier et al. 2013). The wave generator (figure 2) is composed of 8 independent displacement paddles, each 0.5 m wide and 0.5 m deep. It is located at an upstream surface position, in order to create waves propagating with the current.

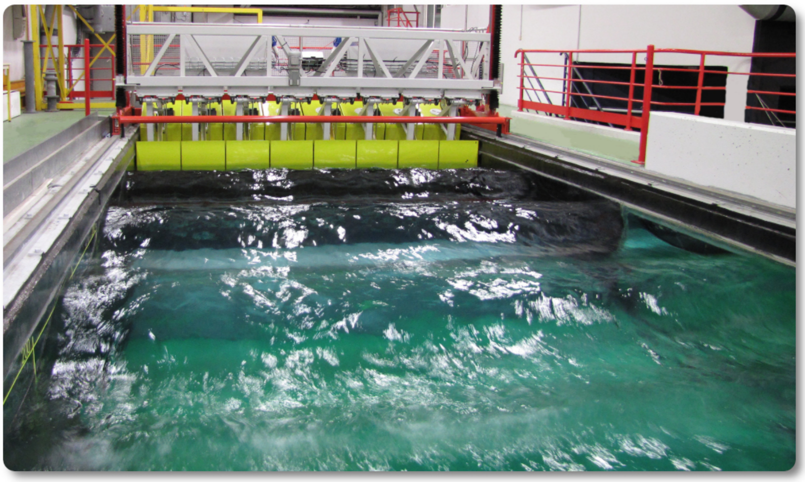

Figure 2 – Wavemaker in the tank

More informations about the flume tank can be found in Gaurier et al. (2018).

2 Instrumentation

2.1 Laser Doppler Velocimeter

This technique enables the measurement of the velocity to be carried out, at a single point in a flow field, with a high temporal resolution. The 2-components LDV system available at IFREMER is composed of 4 laser beams with 2 different wave lengths: 514 nm and 488 nm. The 3-components LDV system includes 6 laser beams with 3 different wave lengths: 514 nm, 488 nm and 532 nm.

Whenever a reflecting particle entrained in the fluid passes through the intersection of two laser beams, the scattered light received from the particle fluctuates in intensity. LDV makes use of the fact that the frequency of this fluctuation is equivalent to the Doppler shift between the incident and scattered light, and is thus proportional to the component of the particle velocity (Dantec Dynamics 2018a). The water of the tank is seeded with particles which should be small enough to follow the flow, yet large enough to scatter sufficient light to obtain a good signal-to-noise ratio. Typically the size of particles used in the IFREMER flume tank is $10\,\mu$m. These particles are spherical and composed of silver coated glass. The data-rate depends on the number of particles detected by the system. The sampling frequency is consequently irregular due to the fact that one measurement value corresponds to one detected particle in the volume.

On the contrary to the 2-components probe, the 3-components LDV measurement is not direct because of the probe shape. Considering the velocity vector $\overrightarrow{U} = u \cdot \vec{e}_x + v \cdot \vec{e}_y + w \cdot \vec{e}_z$, the three components are projected according to the equation 1, with $LDAi$ corresponding to the beam measurements.

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 0.005247 & 1.004515 & -0.005563 \\ 0.038989 & 1.412896 & -1.734007 \\ 0.999819 & -0.013590 & 0.008014 \end{pmatrix} \cdot \begin{pmatrix} LDA1 \\ LDA2 \\ LDA3 \end{pmatrix} \quad (1)$$

Because the 3-components LDV system is used in non-coincident mode, note that before to apply such matrix operation, the $LDAi$ measurements need to be interpolated using the same timestamp.

Finally, the axis system is different between both the LDV facilities. In addition, the 3-components LDV is fixed on a traverse system used to automatically move the measurement point. This traverse system has its own axis orientation, which is again different from the one used for the 2C or 3C LDV. To compare these different axis systems better, schematic 3 depict both the LDV systems and their corresponding axis orientations in the tank.

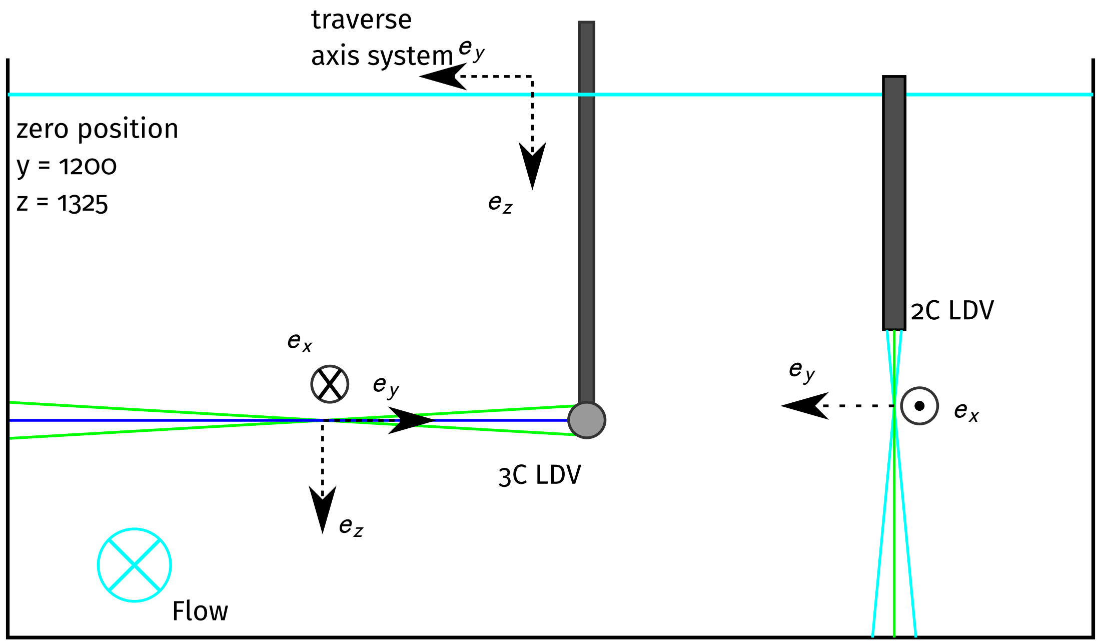

Figure 3 – Schematic of the different axis for both the LDV systems and for the traverse system used to position the 3C-LDV. The zero position corresponds to the y and z coordinates when the 3C-LDV is at the very centre of the tank (same position than the turbine hub).

Finally according to this schematic and considering the 3C-LDV axis system as the main one, the 2C-LDV velocity components can be obtained from equation 2.

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} -LDA1 \\ -LDA2 \end{pmatrix} \quad (2)$$

2.2 Particle Image Velocimetry

The Particle Image Velocimetry system (figure 4) is used as well during these tests (Dantec Dynamics 2018b). The same seeding particles are used for LDV and PIV, into the water. For the PIV measurements a Nd:YAG (Gemini) laser is used with a camera FlowSens EQ-2M, with a resolution of 1600×1200 pixels. The size of the PIV window recorded with this equipment is 0.283×0.378 m^2. This camera acquires a double image with a time step $\delta t = 1200\,\mu$s (for $U_\infty = 0.8$ m/s), in synchronization with the turbine parameters. The acquired data are post-processed with the software Dynamic Studio. The instantaneous velocity filed is calculated using a single-pass cross-correlation method applied on 32×32 pixels interrogation windows with 50 % overlap (Meinhart et al. 1993). Outliers are replaced using the Universal Outlier Detection (UOD) method (Westerweel et al. 2005).

Precisions on the method can be found in Ikhennicheu et al. (2019). The sampling frequency of the system is 15 Hz.

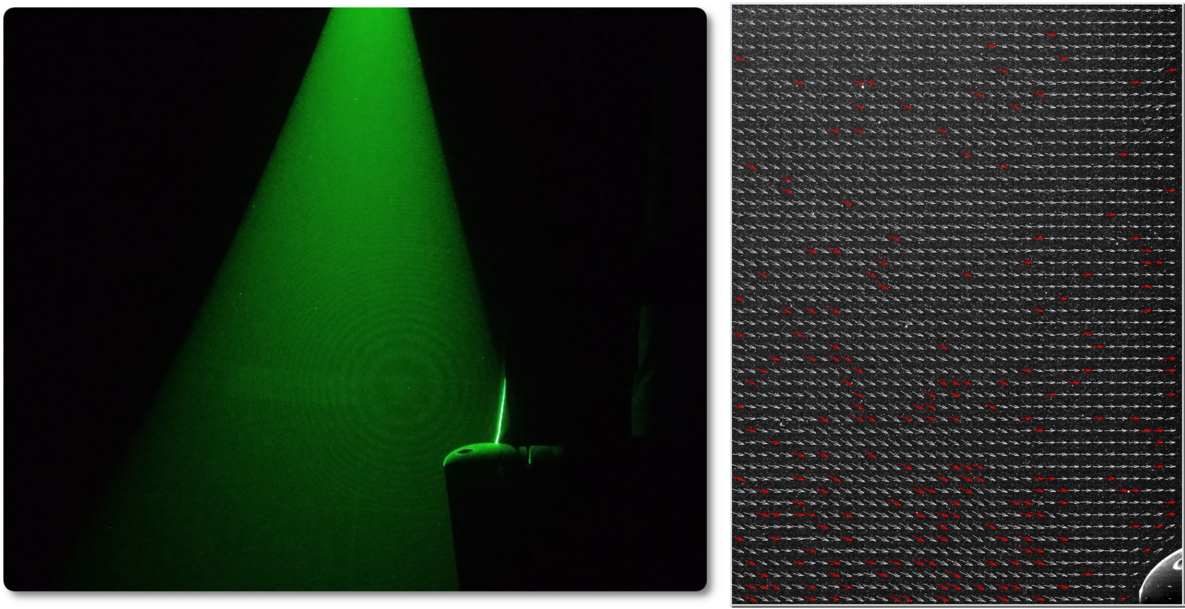

Figure 4 – Particles Image Velocimetry laser map, measuring the flow upstream to the turbine (left) and corresponding instantaneous velocity field (right). The grey arrows stand for the output of the cross-correlation method and the red ones stand for the corrected outliers after applying the Universal Outlier Detection method.

2.3 Marine Current Turbine Model

A 3-bladed turbine model with $D = 700\,\text{mm}$ in diameter (figure 5) is used during these tests. The performance is evaluated using thrust and torque measurements.

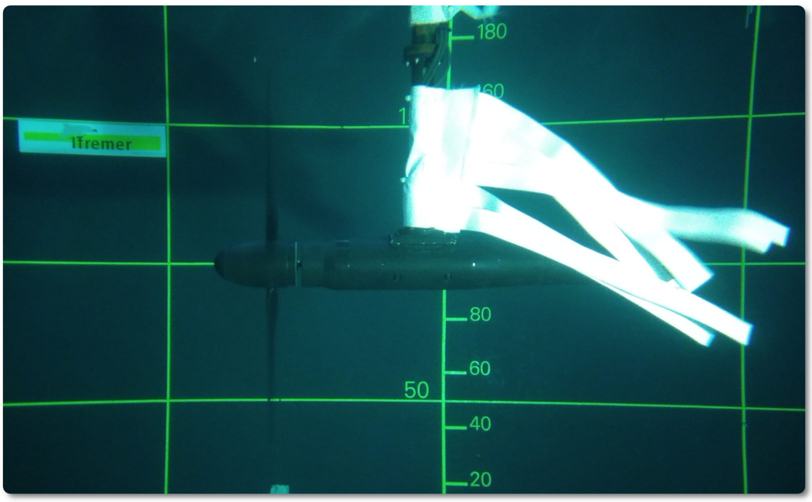

Figure 5 – Marine current turbine model

Three different turbine blade designs are considered in this campaign: T4, T7 and T4-S. All blades use the same aerofoil section (from the NACA 634xx-series, which is representative of a typical industrial design). T4 has a rated TSR of 4 while T7 has a rated TSR of 7. As a result, T7 has much lower blade solidity than T4, creating a more slender blade profile. The T4-S blades have the same rated TSR as T4, with the same solidity and twist, but are swept 30° in the streamwise direction while keeping the wetted inflow area the same as for T4 and T7. The purpose of adding sweep is to reduce the impact of surface waves on the fluctuating turbine loads.

For every test carried out in this dataset, the turbine works under a speed control strategy.

2.4 6-components load-cell and wave gauges

A 6-components load-cell is fixed at the top of the turbine shaft to monitor the forces and moments applied to the turbine.

During the wave and current tests, 3 wave gauges are used to monitor the water level in close proximity to the turbine. One resistive and two dynamic (Kenek) wave gauges are aligned with the current. The distances between the wave gauges are 650 mm between the two dynamic wave gauges and 680 mm between the second dynamic wave gauge and the resistive one (see figure 6). Note that the resistive wave gauge is approximately vertically aligned with the turbine rotor.

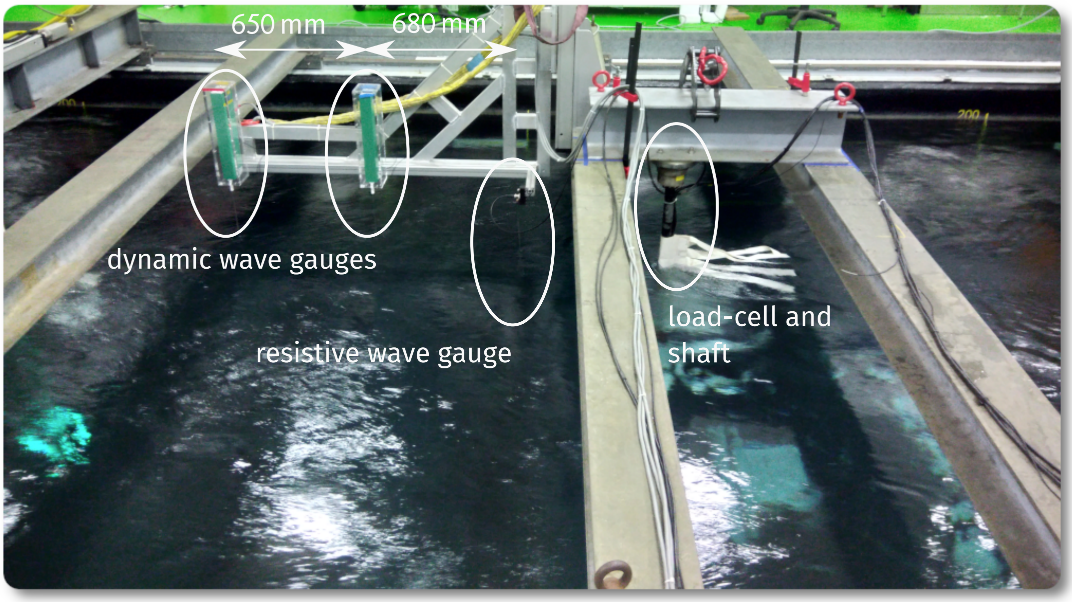

Figure 6 – Location and type of the used wave gauges and position of the 6-components load-cell at the top of the turbine shaft. The current comes from the left to the right. The dynamic wave gauges are named A and B and their relative distance is 650 mm. The resistive wave gauge is approximately vertically aligned with the turbine rotor and its distance to the wave gauge B is 680 mm.

The load-cell and wave gauges acquisition is realized in synchronization with the turbine parameters (torque, thrust and rotation speed).

2.5 Acquisition system

An in-house acquisition software, based on National Instrument Labview programming platform is used to record every sensor: load-cell, turbine parameters and wave gauges.

The acquisition hardware is based on modules PXIe-4339. These modules have a 24 bits resolution, with analogue input channels.

The sampling frequency is constant and the same for all these acquisitions: $f_s = 256$ Hz.

In addition, the LDV or PIV acquisition systems are triggered with the Labview acquisition software when used. This ensures simultaneously start of the recording.

3 Flow characterization

The flow characterization is carried out in empty tank, i.e. without the turbine, but at the exact same location than the rotor. The flow is characterized through LDV and PIV measurements.

3.1 LDV characterization

The 2C-LDV and 3C-LDV systems are first used to take simultaneous 2-point measurements of the flow, at several locations in the turbine plane (figure 7). The 2C-LDV measurement point is always fixed at the location of the turbine hub (0,0); when the 3C-LDV measurement points vary along the 14 points depicted on schematic 7. The purpose is to measure the spatial correlation of turbulent gusts in the turbine plane, by measuring at two locations simultaneously. The main idea is to show how well the inflow at various points correlates with the inflow at the turbine hub. Such measurement are repeated with and without the flow straightener, i.e. with high and low turbulence intensity, for $U_\infty = 0.8$ m/s and without the flow straightener for $U_\infty = 1.2$ m/s. Note that for the lowest turbulence intensity, the number of the measurement points is reduced to 5: the centre (0,0) and the four extremities (0,R), (R,0), (0,-R) and (-R,0).

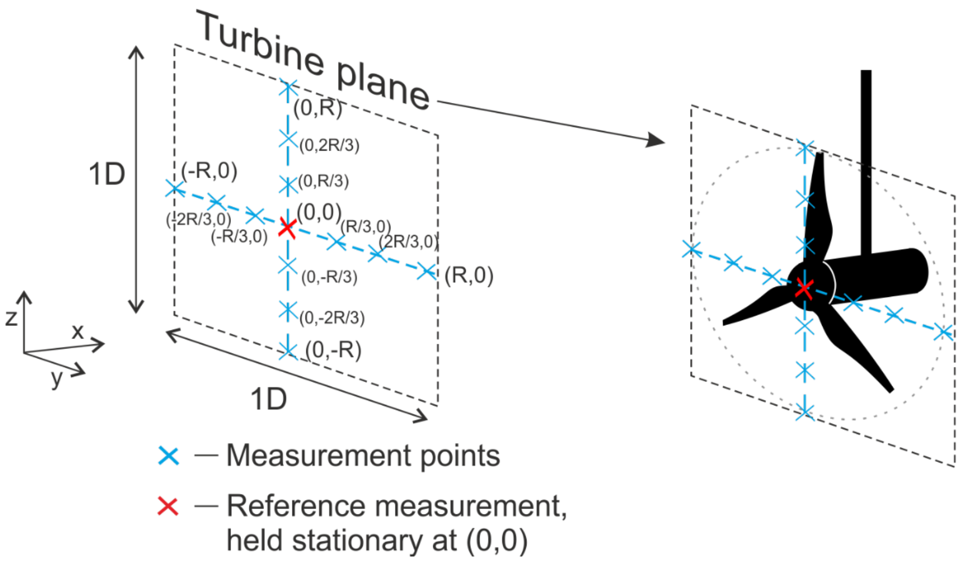

Figure 7 – Locations of the LDV measurement points used for the flow characterization with and without the flow straightener. The 2C-LDV measurement point is always fixed at (0,0) and the 3C-LDV measurement points vary successively and simultaneously along all the displayed points. Note that the axis depicted on this schematic is different from the traverse system axis used to support the 3C-LDV (see figure 3).

The corresponding measurements are named with the basename `cross`. They are stored in the folders `LDV2D/` and `LDV3D/`, depending on the measurement system. The header of these files contains the location of the point, which is expressed in mm. `U08` means $U_\infty \simeq 0.8$ m/s and `TI15` means $I_\infty \simeq 15\,\%$ corresponding to the tank without the flow straightener. On the contrary, `TI02` means $I_\infty \simeq 2\,\%$ which is obtain when the flow straightener is in place.

The inflow velocity in surface waves is measured using the same procedure (2C-LDV and 3C-LDV) at several vertical locations in the turbine plane (figure 8) in the empty tank (turbine not deployed). The reference measurement is done by the 2C-LDV always at the turbine hub height (0,0) in synchronization with the 3C-LDV measuring along the 5 vertical points between (0,-R) and (0,R). For this wave and current flow configuration (with the wavemaker in the tank) it it necessary to characterize the depth-wise variation of the unsteady inflow. Four different waves are successively generated with the current $U_\infty = 0.8$ m/s. The wave frequencies are

0.5, 0.625, 0.75 and 1.0 Hz and the corresponding amplitudes are 100, 130, 130 and 100 mm. These amplitudes correspond to the ones without current. With the current, the wave amplitudes are reduced. That is the reason why the wave measurements are different from these parameters (but the wave frequencies are the same). In addition, the same velocity profile is measured when the wavemaker is parked in the tank, to know the effect of the wavemaker on the vertical velocity shear. The three wave gauges acquire furthermore the surface deformation in synchronization with these LDV measurements.

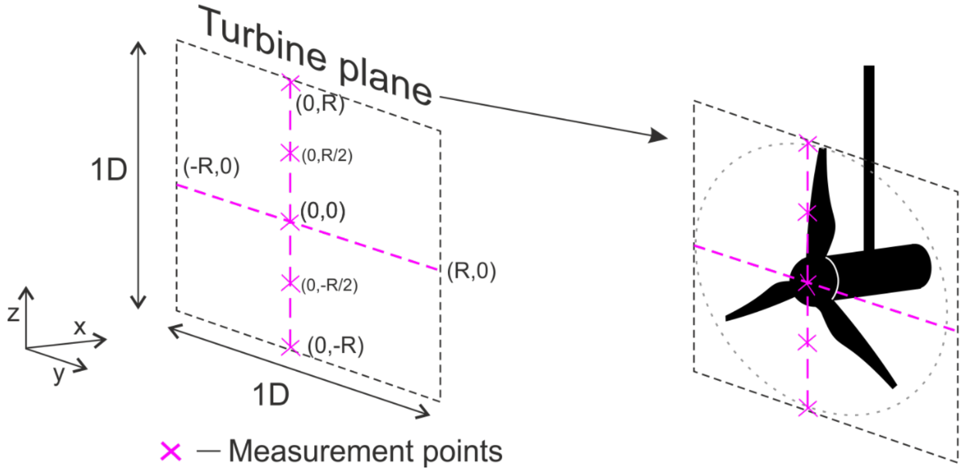

Figure 8 – Locations of the LDV measurement points used for the flow characterization with waves. The 2C-LDV measurement point is always fixed at (0,0) and the 3C-LDV measurement points vary successively and simultaneously along the 5 vertical points. The free surface deformation is measured by the wave gauges as well, in synchronization with the LDV measurements. Note that the axis depicted on this schematic is different from the traverse system axis used to support the 3C-LDV (see figure 3).

Finally, the basename of these measurements is `profile_U08_TI02_wavemaker` for the 2C-LDV and 3C-LDV (in the corresponding folders `LDV2D/` and `LDV3D/`). This basename is followed by the wave frequency or the word `parked` depending on the wave and current configuration. The corresponding wave gauges acquisitions are named `wavemaker` with the run number (see table on figure 14 for details). These files are located in the `LV/` folder and, for each flow configuration, the lowest run number corresponds to the highest LDV acquisition, i.e. (0,R) on schematic 8.

3.2 PIV characterization

The flow has been characterized with the PIV system as well, for $U_\infty = 0.8$ m/s and both the turbulence rates and $U_\infty = 1.2$ m/s and the highest turbulence rate. For the lowest velocity $U_\infty \simeq 0.8$ m/s, 5400 double-images (360 s at $f_s = 15$ Hz) are acquired. For the highest velocity $U_\infty \simeq 1.2$ m/s and the highest turbulence rate $I_\infty \simeq 15$ %, the acquisition time is longer because of the unsteady characteristics of the flow with 9000 double-images (600 s). Two different planes are selected (figure 9):

1. the upper part of the swept area, which is also the one used for the acquisition in synchronization with the turbine parameters (green plan on figure 9);
2. the bottom part of the swept area, corresponding to the same plane size, exactly located 37 cm lower than the upper plane (blue plan on figure 9).

Note that for $U_\infty = 0.8$ m/s and the highest turbulence rate, the 2C-LDV system is located at about 4.2 m upstream to the PIV planes and measures the velocity in synchronization with the PIV measurement (`run072` and `run073`). For $U_\infty = 0.8$ m/s and the lowest turbulence rate, the 2C-LDV is removed from the tank (`run074` and `run075`). For $U_\infty = 1.2$ m/s and $I_\infty \simeq 15$ %, the tank is empty (no 2C-LDV) and the run names are `run185`

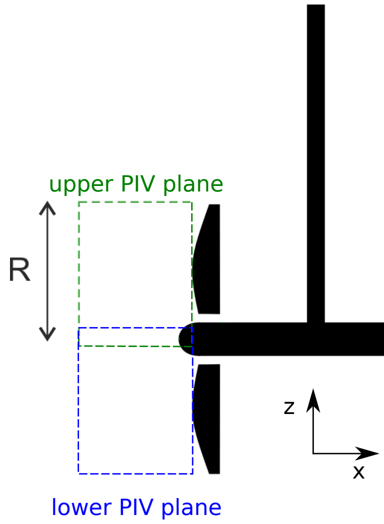

Figure 9 – Location of the upper and lower PIV measurement planes. The upper plane only is used for measurements in synchronization with the turbine parameters. Both planes are successively used for the flow characterization in empty tank (with no turbine).

and `run186`. Run numbers 72, 75 and 185 are acquired at the upper plane and run numbers 73, 74 and 186 are measured at the lower plane (see table on figure 10 for additional details).

4 Turbine measurements

The turbine acquisitions are located in the `LV/` folder. They are constituted of 11 rows (or 14 rows for the wave and current test) including: the thrust T, the torque Q, the rotation speed S, the motor intensity I, the rotation encoder and the 6 load-cell components (F_x, F_y, F_z, M_x, M_y and M_z). For the wave and current tests, the 3 wave gauges are added to the previous rows. All the force and moment data are expressed in N or N m. The wave gauges amplitudes are expressed in mm, the motor rotation speed is expressed in RPM and the motor intensity is expressed in A. The rotation encoder is a trigger sensor producing one positive and one negative voltage fronts per turbine rotation cycle, always for the same angular position. It is recorded with the other channels to be used as a post-processing trigger.

Before every acquisition, a zero file is acquired to remove all the sensor offsets. The corresponding zero is systematically removed from the run files. There is no need to do it again during the post-processing.

Tables displayed on figures 10 to 14 resume all the acquired run files with their corresponding zeros and gives some details and comments about the measurement conditions.

4.1 Performance evaluation with low turbulence

The turbine performance is first evaluated for the lowest turbulence rate ($I_\infty \simeq 2\,\%$) and for $U_\infty = 0.8$ m/s, for the 3 different turbine blades. Run numbers 76 to 105 correspond to these measurements.

The rotation speed varies to cover a Tip Speed Ratio (TSR) range between 0 and 8. TSR is classically defined by formula 3, with ω the rotation speed, R the turbine radius (0.35 m) and U_∞ the far incoming flow velocity.

$$TSR = \frac{\omega R}{U_\infty} \tag{3}$$

For turbine T7 only, the same procedure is applied for a higher flow velocity: $U_\infty = 1.2$ m/s (run numbers 106 to 113).

The acquisition time is constant for all these runs with $T_a = 120\,\mathrm{s}$. The 2C-LDV system is used in synchronization with the turbine parameters to record the incoming flow velocity at $4D$ upstream to the turbine hub.

4.2 Performance evaluation under combined wave and current conditions

The wave and current tests are carried out for turbine T4 and T4-S. The corresponding run numbers are 114 to 178. For all these cases, the flow velocity is always $U_\infty = 0.8\,\mathrm{m/s}$. The wave are created with the current at 4 different frequencies 0.5, 0.625, 0.75 and 1.0 Hz. As described in the previous section, 3 wave gauges measure the surface deformation in synchronization with the turbine parameters. Their relative positions to the turbine are given in figure 6. Because the wavemaker is intrusive in the tank, the incoming flow velocity profile is different with a vertical shear and higher turbulence intensity (see the flow characterization). The turbine response needs to be determined as well for such a particular flow condition. That is the reason why turbine parameters measurements are also performed when the wavemaker is parked.

For all these runs, the TSR range is between 0 and 9 but depends on the tested turbines and on the flow configuration (see table on figures 12 and 13 for details). The acquisition time is constant with $T_a = 240\,\mathrm{s}$.

Again, the 2C-LDV system is used in synchronization for every wave and current run to record the incoming flow velocity at $4D$ upstream to the turbine hub.

4.3 Performance evaluation with high turbulence

The turbine performance is finally quantified for the highest turbulence rate ($I_\infty \simeq 15\,\%$) with PIV measurements in synchronization with the turbine parameters. The PIV measurement is realized in the upper plan (green plane on schematic 9) for all these runs. The corresponding run numbers are 41 to 71 for $U_\infty = 0.8\,\mathrm{m/s}$ and 179 to 184 for $U_\infty = 1.2\,\mathrm{m/s}$. The acquisition time is $T_a = 360\,\mathrm{s}$ for run numbers 41 to 71 and $T_a = 600\,\mathrm{s}$ for run numbers 179 to 184.

The sampling frequency of the PIV acquisition is $f_s = 15\,\mathrm{Hz}$. For run numbers 41 to 54 however, the PIV acquisition is triggered with the turbine rotation frequency: two images are recorded during one rotation cycle corresponding to the positive and negative fronts produced by the encoder. For these runs, the sampling frequency is consequently not constant but depend on the turbine rotation speed. Run numbers 41 to 47 concern turbine T7 and run number 48 to 54 are about turbine T4.

From run numbers 55 to 71, turbines T4, T7 and T4-S are systematically tested in TSR range between 0 and 6. Tests concern finally turbine T7 for run numbers 179 to 183. Only one run (`run184`) is acquired for turbine T4 and for the highest flow velocity ($U_\infty = 1.2\,\mathrm{m/s}$) because the torque sensor is saturated (out of range) for this relatively high flow velocity.

For all these runs, the 2C-LDV system is used as well and located at about 4 m upstream to the turbine hub to quantify the far upstream velocity.

4.4 Additional informations

Please note that the thrust sensor has been damaged during these experiments, water has been found inside the turbine just after `run130`. Signal produced by this sensor from these runs is affected and presents some artefacts which need to me removed.

The load-cell M_y component regularly shows furthermore odd behaviours with unexpected sharp rises. Because all the load-cell components are mathematically linked together (with a global matrix), the load-cell signals processing requires a careful attention.

flow velocity			wave		TSR	acquisition		notes	observations
ind.	vel.	turb.	amp.	freq.		name	zero mode		
[-]	[m/s]	[%]	[mm]	[Hz]		[-]	[-]		
0						zero005	Zero off		turbine T7
620	0.8	15	0	0.000	0.0	run041	Zero on with zero005		trigger PIV twice per rotation
620	0.8	15	0	0.000	2.0	run042	Zero on with zero005		
620	0.8	15	0	0.000	3.0	run043	Zero on with zero005		
620	0.8	15	0	0.000	4.0	run044	Zero on with zero005		LDV upstream @ 6D
620	0.8	15	0	0.000	5.0	run045	Zero on with zero005		
620	0.8	15	0	0.000	6.0	run046	Zero on with zero005		
620	0.8	15	0	0.000	7.0	run047	Zero on with zero005		
0					0.0	zero006	Zero off		turbine T4
620	0.8	15	0	0.000	0.0	run048	Zero on with zero006		trigger PIV twice per rotation
620	0.8	15	0	0.000	1.0	run049	Zero on with zero006		LDV upstream @ 6D
620	0.8	15	0	0.000	2.0	run050	Zero on with zero006		
620	0.8	15	0	0.000	3.0	run051	Zero on with zero006		
620	0.8	15	0	0.000	4.0	run052	Zero on with zero006		
620	0.8	15	0	0.000	5.0	run053	Zero on with zero006		
620	0.8	15	0	0.000	6.0	run054	Zero on with zero006		
620	0.8	15	0	0.000	1.0	run055	Zero on with zero006		turbine T4
620	0.8	15	0	0.000	2.0	run056	Zero on with zero006		PIV @ 15 Hz
620	0.8	15	0	0.000	3.0	run057	Zero on with zero006		LDV upstream @ 6D
620	0.8	15	0	0.000	4.0	run058	Zero on with zero006		
620	0.8	15	0	0.000	5.0	run059	Zero on with zero006		
0					0.0	zero007	Zero off		turbine T7
620	0.8	15	0	0.000	0.0	run060	Zero on with zero007		PIV @ 15 Hz
620	0.8	15	0	0.000	2.0	run061	Zero on with zero007		LDV upstream @ 6D
620	0.8	15	0	0.000	3.0	run062	Zero on with zero007		
620	0.8	15	0	0.000	4.0	run063	Zero on with zero007		
620	0.8	15	0	0.000	5.0	run064	Zero on with zero007		
620	0.8	15	0	0.000	6.0	run065	Zero on with zero007		
0					0.0	zero008	Zero off		turbine T4-S
620	0.8	15	0	0.000	0.0	run066	Zero on with zero008		PIV @ 15 Hz
620	0.8	15	0	0.000	1.0	run067	Zero on with zero008		LDV upstream @ 6D
620	0.8	15	0	0.000	2.0	run068	Zero on with zero008		
620	0.8	15	0	0.000	3.0	run069	Zero on with zero008		
620	0.8	15	0	0.000	4.0	run070	Zero on with zero008		
620	0.8	15	0	0.000	5.0	run071	Zero on with zero008		
620	0.8	15	0	0.000		run072		without turbine top	PIV @ 15 Hz
620	0.8	15	0	0.000		run073		without turbine bottom (z-37cm)	LDV upstream @ 6D
662	0.8	1.5	0	0.000		run074		without turbine bottom (z-37cm)	PIV @ 15 Hz
662	0.8	1.5	0	0.000		run075		without turbine top	Without LDV

Figure 10 – Details on the run numbers 41 to 75 carried out with the PIV system in synchronization with the turbine parameters for the high turbulence rate ($I_\infty \simeq 15\,\%$) and for $U_\infty = 0.8\,\mathrm{m/s}$. Run numbers 72 to 75 are acquired in the empty tank (no turbine) for characterizing the flow. Only run number 74 and 75 are recorded for the lowest turbulence rate ($I_\infty \simeq 2\,\%$).

flow velocity			wave		TSR	acquisition		notes	observations
ind.	vel.	turb.	amp.	freq.		name	zero mode		
[-]	[m/s]	[%]	[mm]	[Hz]		[-]	[-]		
0						zero009	Zero off		turbine T4-S
662	0.8	1.5	0	0.000	0.0	run076	Zero on with zero009		LDV upstream @ 4D
662	0.8	1.5	0	0.000	1.0	run077	Zero on with zero009		
662	0.8	1.5	0	0.000	1.5	run078	Zero on with zero009		
662	0.8	1.5	0	0.000	2.0	run079	Zero on with zero009		
662	0.8	1.5	0	0.000	2.5	run080	Zero on with zero009		
662	0.8	1.5	0	0.000	3.0	run081	Zero on with zero009		
662	0.8	1.5	0	0.000	4.0	run082	Zero on with zero009		
662	0.8	1.5	0	0.000	5.0	run083	Zero on with zero009		
662	0.8	1.5	0	0.000	6.0	run084	Zero on with zero009		
662	0.8	1.5	0	0.000	7.0	run085	Zero on with zero009		
0					0.0	zero010	Zero off		turbine T4
662	0.8	1.5	0	0.000	0.0	run086	Zero on with zero010		LDV upstream @ 4D
662	0.8	1.5	0	0.000	1.0	run087	Zero on with zero010		
662	0.8	1.5	0	0.000	1.5	run088	Zero on with zero010		
662	0.8	1.5	0	0.000	2.0	run089	Zero on with zero010		
662	0.8	1.5	0	0.000	2.5	run090	Zero on with zero010		
662	0.8	1.5	0	0.000	3.0	run091	Zero on with zero010		
662	0.8	1.5	0	0.000	4.0	run092	Zero on with zero010		
662	0.8	1.5	0	0.000	5.0	run093	Zero on with zero010		
662	0.8	1.5	0	0.000	6.0	run094	Zero on with zero010		
662	0.8	1.5	0	0.000	7.0	run095	Zero on with zero010		
0					0.0	zero011	Zero off		turbine T7
662	0.8	1.5	0	0.000	0.0	run096	Zero on with zero011		LDV upstream @ 4D
662	0.8	1.5	0	0.000	2.0	run097	Zero on with zero011		
662	0.8	1.5	0	0.000	3.0	run098	Zero on with zero011		
662	0.8	1.5	0	0.000	3.5	run099	Zero on with zero011		
662	0.8	1.5	0	0.000	4.0	run100	Zero on with zero011		
662	0.8	1.5	0	0.000	4.5	run101	Zero on with zero011		
662	0.8	1.5	0	0.000	5.0	run102	Zero on with zero011		
662	0.8	1.5	0	0.000	6.0	run103	Zero on with zero011		
662	0.8	1.5	0	0.000	7.0	run104	Zero on with zero011		
662	0.8	1.5	0	0.000	8.0	run105	Zero on with zero011		

Figure 11 – Details on the run numbers 76 to 105 carried out for quantifying the three turbine performances for the lowest turbulence rate ($I_\infty \simeq 2\,\%$) and for $U_\infty = 0.8\,\mathrm{m/s}$

flow velocity			wave		TSR	acquisition		notes	observations
ind.	vel.	turb.	amp.	freq.		name	zero mode		
[-]	[m/s]	[%]	[mm]	[Hz]		[-]	[-]		
0					0.0	zero012	Zero off		turbine T7
992	1.2	1.5	0	0.000	0.0	run106	Zero on with zero012		LDV upstream @ 4D
992	1.2	1.5	0	0.000	2.0	run107	Zero on with zero012		
992	1.2	1.5	0	0.000	3.0	run108	Zero on with zero012		
992	1.2	1.5	0	0.000	4.0	run109	Zero on with zero012		
992	1.2	1.5	0	0.000	5.0	run110	Zero on with zero012		
992	1.2	1.5	0	0.000	6.0	run111	Zero on with zero012		
992	1.2	1.5	0	0.000	7.0	run112	Zero on with zero012		
992	1.2	1.5	0	0.000	8.0	run113	Zero on with zero012		
0					0.0	zero013	Zero off		turbine T7
662	0.8	1.5	0	parked	0.0	run114	Zero on with zero013		Parked wavemaker
662	0.8	1.5	0	parked	1.5	run115	Zero on with zero013		LDV upstream @ 4D
662	0.8	1.5	0	parked	3.0	run116	Zero on with zero013		
662	0.8	1.5	0	parked	4.5	run117	Zero on with zero013		
662	0.8	1.5	0	parked	6.0	run118	Zero on with zero013		
662	0.8	1.5	0	parked	7.5	run119	Zero on with zero013		
662	0.8	1.5	0	parked	9.0	run120	Zero on with zero013		
662	0.8	1.5	100	0.500	0.0	run121	Zero on with zero013		turbine T7
662	0.8	1.5	100	0.500	3.0	run122	Zero on with zero013		Wave 0.5 Hz
662	0.8	1.5	100	0.500	4.5	run123	Zero on with zero013		LDV upstream @ 4D
662	0.8	1.5	100	0.500	6.0	run124	Zero on with zero013		
662	0.8	1.5	100	0.500	7.5	run125	Zero on with zero013		
662	0.8	1.5	130	0.625	0.0	run126	Zero on with zero013		turbine T7
662	0.8	1.5	130	0.625	3.0	run127	Zero on with zero013		Wave 0.625 Hz
662	0.8	1.5	130	0.625	4.5	run128	Zero on with zero013		LDV upstream @ 4D
662	0.8	1.5	130	0.625	6.0	run129	Zero on with zero013		
662	0.8	1.5	130	0.625	7.5	run130	Zero on with zero013		
0					0.0	zero014	Zero off		turbine T4
662	0.8	1.5	0	parked	0.0	run131	Zero on with zero014		Parked wavemaker
662	0.8	1.5	0	parked	1.0	run132	Zero on with zero014		LDV upstream @ 4D
662	0.8	1.5	0	parked	2.0	run133	Zero on with zero014		
662	0.8	1.5	0	parked	3.0	run134	Zero on with zero014		
662	0.8	1.5	0	parked	4.0	run135	Zero on with zero014		
662	0.8	1.5	0	parked	5.0	run136	Zero on with zero014		
662	0.8	1.5	0	parked	6.0	run137	Zero on with zero014		
662	0.8	1.5	0	parked	7.0	run138	Zero on with zero014		
662	0.8	1.5	100	0.500	2.0	run139	Zero on with zero014		turbine T4
662	0.8	1.5	100	0.500	3.0	run140	Zero on with zero014		Wave 0.5 Hz
662	0.8	1.5	100	0.500	4.0	run141	Zero on with zero014		LDV upstream @ 4D
662	0.8	1.5	100	0.500	5.0	run142	Zero on with zero014		

Figure 12 – Details on run numbers 106 to 142. Run numbers 106 to 113 are carried out to quantify the turbine T7 performance for a higher flow velocity with $U_\infty = 1.2\,\mathrm{m/s}$. Run numbers 114 to 142 constitute the first wave and current tests for turbines T7 and T4.

flow velocity			wave		TSR	acquisition		notes	observations
ind.	vel.	turb.	amp.	freq.		name	zero mode		
[-]	[m/s]	[%]	[mm]	[Hz]		[-]	[-]		
662	0.8	1.5	130	0.625	2.0	run143	Zero on with zero014		turbine T4
662	0.8	1.5	130	0.625	3.0	run144	Zero on with zero014		Wave 0.625 Hz
662	0.8	1.5	130	0.625	4.0	run145	Zero on with zero014		LDV upstream @ 4D
662	0.8	1.5	130	0.625	5.0	run146	Zero on with zero014		
662	0.8	1.5	130	0.750	2.0	run147	Zero on with zero014		turbine T4
662	0.8	1.5	130	0.750	3.0	run148	Zero on with zero014		Wave 0.750 Hz
662	0.8	1.5	130	0.750	4.0	run149	Zero on with zero014		LDV upstream @ 4D
662	0.8	1.5	130	0.750	5.0	run150	Zero on with zero014		
662	0.8	1.5	100	1.000	2.0	run151	Zero on with zero014		turbine T4
662	0.8	1.5	100	1.000	3.0	run152	Zero on with zero014		Wave 1.000 Hz
662	0.8	1.5	100	1.000	4.0	run153	Zero on with zero014		LDV upstream @ 4D
662	0.8	1.5	100	1.000	5.0	run154	Zero on with zero014		
0					0.0	zero015	Zero off		turbine T4-S
662	0.8	1.5	0	parked	0.0	run155	Zero on with zero015		Parked wavemaker
662	0.8	1.5	0	parked	1.0	run156	Zero on with zero015		LDV upstream @ 4D
662	0.8	1.5	0	parked	2.0	run157	Zero on with zero015		
662	0.8	1.5	0	parked	3.0	run158	Zero on with zero015		
662	0.8	1.5	0	parked	4.0	run159	Zero on with zero015		
662	0.8	1.5	0	parked	5.0	run160	Zero on with zero015		
662	0.8	1.5	0	parked	6.0	run161	Zero on with zero015		
662	0.8	1.5	0	parked	7.0	run162	Zero on with zero015		
662	0.8	1.5	100	0.500	2.0	run163	Zero on with zero015		turbine T4-S
662	0.8	1.5	100	0.500	3.0	run164	Zero on with zero015		Wave 0.5 Hz
662	0.8	1.5	100	0.500	4.0	run165	Zero on with zero015		LDV upstream @ 4D
662	0.8	1.5	100	0.500	5.0	run166	Zero on with zero015		
0					0.0	zero016	Zero off		turbine T4-S
662	0.8	1.5	130	0.625	2.0	run167	Zero on with zero016		Wave 0.625 Hz
662	0.8	1.5	130	0.625	3.0	run168	Zero on with zero016		LDV upstream @ 4D
662	0.8	1.5	130	0.625	4.0	run169	Zero on with zero016		
662	0.8	1.5	130	0.625	5.0	run170	Zero on with zero016		
662	0.8	1.5	130	0.750	2.0	run171	Zero on with zero016		turbine T4-S
662	0.8	1.5	130	0.750	3.0	run172	Zero on with zero016		Wave 0.750 Hz
662	0.8	1.5	130	0.750	4.0	run173	Zero on with zero016		LDV upstream @ 4D
662	0.8	1.5	130	0.750	5.0	run174	Zero on with zero016		
662	0.8	1.5	100	1.000	2.0	run175	Zero on with zero016		turbine T4-S
662	0.8	1.5	100	1.000	3.0	run176	Zero on with zero016		Wave 1.000 Hz
662	0.8	1.5	100	1.000	4.0	run177	Zero on with zero016		LDV upstream @ 4D
662	0.8	1.5	100	1.000	5.0	run178	Zero on with zero016		

Figure 13 – Details on run numbers 143 to 178 carried out with wave and current for turbine T4 and T4-S.

flow velocity			wave		TSR	acquisition		notes	observations
ind.	vel.	turb.	amp.	freq.		name	zero mode		
[-]	[m/s]	[%]	[mm]	[Hz]		[-]	[-]		
0	0	0				zero017	Zero off		parked wavemaker
662	0.8	1.5	0	parked		wavemaker001	Zero on with zero017		LDV upstream @ 4D
662	0.8	1.5	0	parked		wavemaker002	Zero on with zero017		
662	0.8	1.5	0	parked		wavemaker003	Zero on with zero017		
662	0.8	1.5	0	parked		wavemaker004	Zero on with zero017		
662	0.8	1.5	0	parked		wavemaker005	Zero on with zero017		
0	0	0				zero018	Zero off		
662	0.8	1.5	100	0.500		wavemaker007	Zero on with zero018		
662	0.8	1.5	100	0.500		wavemaker008	Zero on with zero018		Wave 0.5Hz
662	0.8	1.5	100	0.500		wavemaker009	Zero on with zero018		LDV upstream @ 4D
662	0.8	1.5	100	0.500		wavemaker010	Zero on with zero018		
662	0.8	1.5	100	0.500		wavemaker011	Zero on with zero018		
662	0.8	1.5	130	0.625		wavemaker012	Zero on with zero018		
662	0.8	1.5	130	0.625		wavemaker013	Zero on with zero018		Wave 0.625Hz
662	0.8	1.5	130	0.625		wavemaker014	Zero on with zero018		LDV upstream @ 4D
662	0.8	1.5	130	0.625		wavemaker015	Zero on with zero018		
662	0.8	1.5	130	0.625		wavemaker016	Zero on with zero018		
662	0.8	1.5	130	0.750		wavemaker017	Zero on with zero018		
662	0.8	1.5	130	0.750		wavemaker018	Zero on with zero018		Wave 0.750Hz
662	0.8	1.5	130	0.750		wavemaker019	Zero on with zero018		LDV upstream @ 4D
662	0.8	1.5	130	0.750		wavemaker020	Zero on with zero018		
662	0.8	1.5	130	0.750		wavemaker021	Zero on with zero018		
662	0.8	1.5	100	1.000		wavemaker022	Zero on with zero018		
662	0.8	1.5	100	1.000		wavemaker023	Zero on with zero018		Wave 1.000Hz
662	0.8	1.5	100	1.000		wavemaker024	Zero on with zero018		LDV upstream @ 4D
662	0.8	1.5	100	1.000		wavemaker025	Zero on with zero018		
662	0.8	1.5	100	1.000		wavemaker026	Zero on with zero018		
0	0	0	0	0.000		zero019	Zero off		turbine T7
930	1.2	15	0	0.000	3.0	run179	Zero on with zero019		PIV @ 15 Hz
930	1.2	15	0	0.000	4.0	run180	Zero on with zero019		
930	1.2	15	0	0.000	5.0	run181	Zero on with zero019		
930	1.2	15	0	0.000	6.0	run182	Zero on with zero019		
930	1.2	15	0	0.000	7.0	run183	Zero on with zero019		
0	0	0	0	0.000		zero020	Zero off		turbine T4
930	1.2	15	0	0.000	3.0	run184	Zero on with zero020		PIV @ 15 Hz
930	1.2	15	0	0.000		run185		without turbine top	PIV @ 15 Hz
930	1.2	15	0	0.000		run186		without turbine bottom (z-37cm)	Without LDV

Figure 14 – Details on tests `wavemaker001` to `wavemaker026` carried out to characterize the wave and current conditions in the empty tank (no turbine). These tests involve the wave gauges in synchronization with the 2C-LDV. Turbines T7 and T4 are tested then for run numbers 179 to 184, for the highest flow velocity $U_\infty = 1.2\,\mathrm{m/s}$ and for the highest turbulence rate ($I_\infty \simeq 15\,\%$). The flow characterization is finally performed with the PIV for the same flow configuration in the empty tank (no turbine) for run numbers 185 and 186.

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