Three tidal turbines in interaction: an experimental data-set on wake and performances

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I. Experimental set-up

The present data-set deals with the characterisation of the interaction effects between three marine current turbines. The trials were carried out in the IFREMER wave and current flume tank. This tank working section is $18m$ long by $4m$ wide and $2m$ deep. The stream-wise flow velocity range is 0.1 to $2.2m/s$.

The concerned configuration is two upstream turbines perpendicular to the upstream flow direction and a third turbine downstream, as shown on figure 2. Three configurations have been tested for the transverse position of the downstream turbine, as explained in table I. The turbine diameter is $D = 0.7m$ and the far upstream velocity is $U_\infty = 0.8m/s$, for all the provided tests.

Table I: Summary of the geometrical configuration. a, b_1 and b_2 refer to the schematic 2

Config. name	a	b_1	b_2
config1	$4D$	$2D$	$1D$
config2	$4D$	$2D$	$0.75D$
config3	$4D$	$2D$	$0.5D$

Following the previous work dealing with a single turbine [1] and two interacting turbines axially aligned with the flow direction [2], these new experiments focus on 3 turbines in interaction (figure 1).

The three turbines used for this work are all identical, in terms of geometry (blades, hub and nacelle) and rotor speed control unit. However, in this set of experiments, the turbines are slightly different from those used in the former studies [1], [2]: all the blades were re-manufactured and the blade binding or fastening device was redesigned. The blades profile, detailed in [3], is designed based on a NACA 63418 and the global pitch angle is set to 0 degree.

II. Turbine performances

Only the downstream turbine is instrumented in order to quantify the interaction effects. The turbine parameter acquisition time is set to $T_{turb} = 180s$. The turbine is equipped with a torquemeter located between the rotor and the motor, on the rotation axis. In addition, a six components load-cell is used at the top of the shaft (see figures 1 and 2) measuring the 3 forces and 3 moments applied on the turbine and mast. The motor of the turbine is equipped with an encoder enables the rotation speed to be measured. The rotation speed is normalized with the classical Tip Speed Ratio number:

$$TSR = \frac{\omega R}{U_\infty} \quad (1)$$

with ω the rotation speed and $R = D/2 = 0.35m$ the turbine radius. For all of the tested cases, the upstream turbines TSR is fixed at the maximum of the power extraction: $TSR = 3.5$. Then, the downstream TSR varies between $TSR = 0$ to $TSR = 7$.

All the data coming from the turbine are collected with a sampling frequency of $f_s = 100Hz$.

III. Flow measurements

The flow velocity measurements are performed by means of a bi-dimensional Laser Doppler Velocimetry (LDV) system. This system records the particles velocity where the laser beams cross. Thus, the velocity acquisition is performed with an irregular sampling rate. The measurement volume is an ellipsoid with a $0.12mm$ diameter and $2.51mm$ high, which leads to about $0.01mm^3$. The measurement duration on each point is $T_{LDV} = 180s$ with a quite high data-rate.

The LDV measurements are performed along transverse profiles, from distance $X = 1.2D$ to $X = 11D$, from the upstream turbines row. Each profile is discretized with different number of points depending on

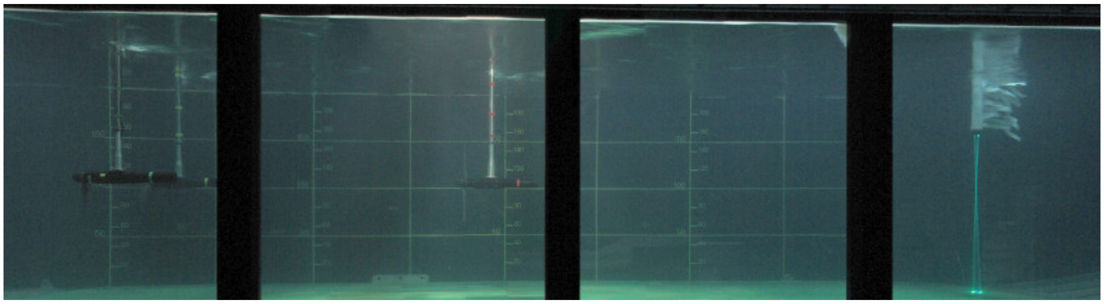

Figure 1: View of the experimental set-up in the tank, during a LDV measurement

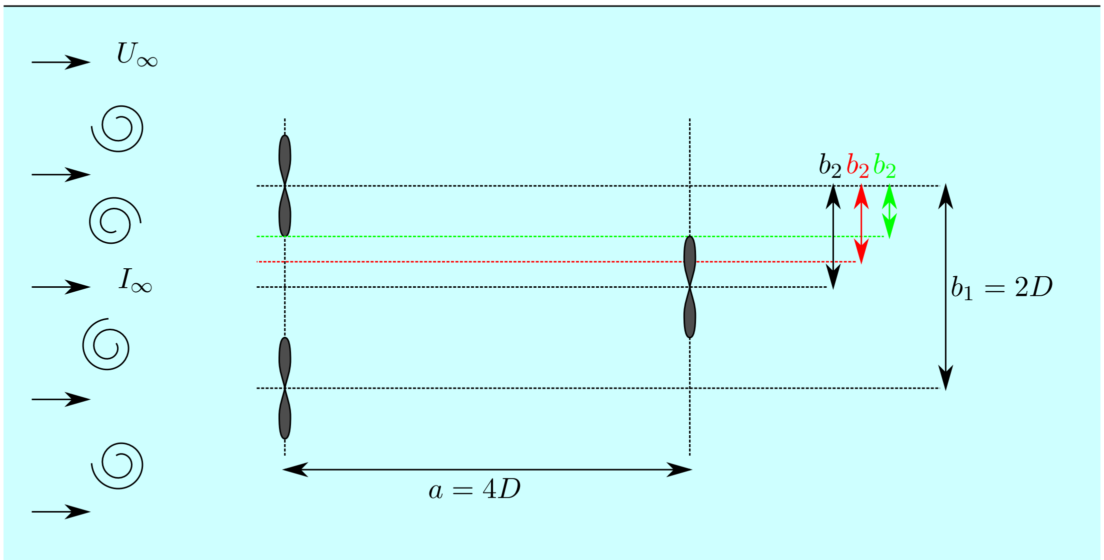

Figure 2: Schematic of experimental set-up

the refinement requirement, in function of the turbines positions and velocity gradients.

During all these measurements, the three turbines were at $TSR = 3.5$.

IV. Turbulence effect

For these measurements, two different ambient turbulence conditions are considered. The turbulence in the flume tank is induced by the current generation system. As a matter of fact, without the use of flow straightener, the natural ambient turbulence intensity of the flow is the highest at $I_\infty \simeq 15\%$. A smoother flow may be obtained by the use of straightener and grid, reducing the turbulence intensity rate to about $I_\infty \simeq 1.3\%$.

The lowest turbulent rate is different from previous studies, as in [4] where it was $I_\infty \simeq 3\%$. This difference is due to the use of a new grid upstream of the flow straightener in order to correct the asymmetry of the upstream velocity in the flume tank. As a consequence, the turbulence intensity rate is slightly reduced.

Because of the removing of grid and flow straightener between the two different turbulent rates, the far upstream velocity is slightly different. The analysis of the upstream velocity profile has shown especially that $U_\infty = 0.79 m/s$ for $I_\infty = 1.3\%$ and $U_\infty = 0.83 m/s$ for $I_\infty = 15\%$.

V. Informations on the files

The provided files are organized in two different folders, corresponding to flow measurements and turbine performances. Inside each one, there are 6 sub-folders named `config1_TI15` for instance. That means the results inside this folder deals with the 3 turbines in configuration 1 (see table I) and with an incoming flow turbulent intensity of $I_\infty \simeq 15\%$.

The content of the performance files are constituted of 12 columns including:

- the 6 components of the load-cell: F_x, F_y, F_z, M_x, M_y and M_z, expressed in N for forces and $N.m$

for moments, located on the mast of the downstream turbine

- the 3 turbines RPM: starboard side, port side for the upstream line and the downstream turbine
- the torque for the downstream turbine expressed in $N.m$
- the motor current and the demand current recorded for internal control, but not useful for this study, both expressed in V

The content of the laser (LDV) files are constituted of 7 columns including:

- the row number
- the Arrival Time (AT) in ms, the Transit Time (TT) in μs and the value of the particle velocity in m/s for the first component of the velocity: $u.e_x$
- the Arrival Time (AT) in ms, the Transit Time (TT) in μs and the value of the particle velocity in m/s for the second component of the velocity: $v.e_y$

The Arrival Time is the time at which the particle has been seen by the laser. The Transit Time is the time during which the particle stays in the measurement volume.

Because the laser is in non-coincident mode, the number of particles perceived by each component is different. A particular attention has to be made for the second component of the velocity which has usually a lower number of values: its corresponding columns are filled-in with zeros in order to have the same length than the other component.

The following pages sum up all the provided files for the performance tests and give their corresponding name and testing configuration.

References

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[3] B. Gaurier, G. Germain, J.-V. Facq, C. Johnstone, A. Grant, A. Day, E. Nixon, F. Di Felice, and M. Costanzo, "Tidal energy "Round Robin" tests comparisons between towing tank and circulating tank results," *International Journal of Marine Energy*, vol. 12, pp. 87 – 109, 2015, special Issue on Marine Renewables Infrastructure Network. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2214166915000223

[4] O. Durán Medina, F. G. Schmitt, R. Calif, G. Germain, and B. Gaurier, "Turbulence analysis and multiscale correlations between synchronized flow velocity and marine turbine power production," *Renewable Energy*, vol. 112, pp. 314 – 327, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960148117304093

Runs	***TSR***	***Fx***	***Fy***	***Fz***	***Mx***	***My***	***Mz***	***RPM starboard***	***RPM port***	***RPM downstream***	***Torque***	***Motor current***	***Demand current***
	[-]	[N]	[N]	[N]	[N.m]	[N.m]	[N.m]	[RPM]	[RPM]	[RPM]	[N.m]	[V]	[V]
configuration 1 - TI = 15%													
zero01		-0.4	0.4	0.7	0.2	0.0	-0.1	0.0	-0.1	-0.46	0.01	0.03	-0.01
run001	0.0	**30.81**	-2.05	0.70	0.41	38.41	-1.29	76.79	76.84	**-0.50**	**-0.60**	-0.128	-0.008
run002	1.0	**40.94**	-3.27	0.45	1.02	52.12	-1.54	76.79	76.84	**21.62**	**-0.71**	-0.130	0.623
run003	2.0	**61.89**	-4.29	0.60	0.21	82.35	-2.20	76.79	76.83	**43.58**	**-1.94**	-0.451	1.250
run004	2.5	**74.06**	-4.63	0.60	-1.16	99.52	-2.80	76.78	76.82	**54.56**	**-3.26**	-0.798	1.562
run005	3.0	**87.32**	-5.39	0.71	-1.92	118.48	-3.25	76.78	76.82	**65.38**	**-4.34**	-1.096	1.871
run006	3.5	**101.46**	-5.92	1.30	-2.06	138.03	-3.71	76.77	76.83	**76.22**	**-4.45**	-1.141	2.181
run007	4.0	**108.11**	-7.06	0.67	-0.35	147.30	-4.02	76.77	76.82	**87.11**	**-3.84**	-0.974	2.491
run008	4.5	**117.12**	-6.93	1.02	-0.25	160.48	-4.38	76.77	76.82	**98.34**	**-3.35**	-0.843	2.812
run009	5.0	**118.70**	-7.73	0.92	1.07	162.52	-4.44	76.76	76.81	**109.20**	**-2.52**	-0.618	3.122
run010	5.5	**124.74**	-8.08	1.12	1.43	171.36	-4.55	76.76	76.81	**120.04**	**-2.28**	-0.560	3.432
run011	6.0	**127.02**	-8.04	1.23	1.66	175.14	-4.41	76.75	76.81	**130.86**	**-1.83**	-0.432	3.741
run012	7.0	**131.32**	-8.44	1.11	3.01	181.09	-4.52	76.75	76.81	**153.00**	**-1.02**	-0.184	4.372
configuration 2 - TI = 15%													
zero02		0.8	0.4	0.3	0.2	0.1	-0.1	0.0	-0.1	-0.47	-0.06	0.01	-0.01
run013	0.0	**33.95**	-3.55	0.25	1.97	40.46	-1.29	77.00	77.06	**-0.48**	**-0.61**	-0.119	-0.008
run014	1.0	**41.94**	-3.36	0.43	1.06	51.74	-1.67	76.98	77.05	**21.55**	**-0.68**	-0.131	0.621
run015	2.0	**64.07**	-4.40	0.65	-0.14	83.11	-2.53	76.98	77.04	**43.61**	**-1.87**	-0.442	1.250
run016	2.5	**75.72**	-5.28	0.11	-0.61	99.62	-3.07	76.97	77.03	**54.55**	**-3.10**	-0.759	1.561
run017	3.0	**88.01**	-6.17	0.56	-1.05	117.31	-3.47	76.97	77.03	**65.33**	**-4.03**	-1.009	1.870
run018	3.5	**100.30**	-6.77	0.86	-0.73	134.78	-3.92	76.97	77.03	**76.35**	**-4.12**	-1.039	2.184
run019	4.0	**108.32**	-7.63	0.65	0.63	145.48	-4.39	76.97	77.02	**87.15**	**-3.66**	-0.916	2.492
run020	4.5	**114.08**	-7.64	1.38	0.80	153.62	-4.45	76.97	77.03	**98.21**	**-3.18**	-0.790	2.809

run021	5.0	**118.52**	-7.93	1.52	1.35	160.03	-4.48	76.96	77.02	**109.12**	**-2.72**	-0.671	3.119
run022	5.5	**120.86**	-8.63	1.22	2.61	163.25	-4.64	76.96	77.02	**119.98**	**-2.19**	-0.533	3.431
run023	6.0	**128.02**	-8.71	1.56	2.62	173.70	-4.73	76.95	77.00	**130.89**	**-1.99**	-0.468	3.741
run024	7.0	**130.92**	-9.18	1.65	3.86	177.49	-4.79	76.95	77.02	**152.77**	**-1.12**	-0.215	4.366
configuration 3 - TI = 15%													
zero03		0.6	0.7	0.4	0.2	0.2	-0.1	0.0	-0.1	-0.47	-0.04	0.01	-0.01
run025	0.0	**32.30**	-2.83	0.69	1.18	38.39	-1.29	76.73	76.80	**-0.48**	**-0.58**	-0.130	-0.008
run026	1.0	**42.17**	-3.14	0.57	1.02	51.73	-1.67	76.73	76.79	**21.53**	**-0.67**	-0.126	0.620
run027	2.0	**64.04**	-3.76	0.66	-0.29	82.69	-2.67	76.72	76.78	**43.66**	**-1.93**	-0.451	1.251
run028	2.5	**75.42**	-4.97	0.02	-0.52	98.59	-3.11	76.72	76.77	**54.48**	**-3.23**	-0.790	1.560
run029	3.0	**86.17**	-5.85	0.35	-0.35	113.90	-3.40	76.72	76.78	**65.38**	**-3.99**	-0.996	1.871
run030	3.5	**98.88**	-6.96	0.95	0.51	131.39	-3.67	76.71	76.77	**76.24**	**-4.04**	-1.018	2.181
run031	4.0	**104.44**	-6.66	1.22	0.23	139.83	-3.92	76.71	76.77	**87.10**	**-3.52**	-0.883	2.491
run032	4.5	**111.73**	-7.31	1.46	1.11	149.31	-4.14	76.70	76.76	**98.27**	**-3.06**	-0.762	2.810
run033	5.0	**114.56**	-7.66	1.35	1.95	153.49	-4.46	76.69	76.76	**109.09**	**-2.51**	-0.616	3.120
run034	5.5	**120.76**	-8.40	1.45	2.80	162.09	-4.68	76.69	76.76	**119.96**	**-2.17**	-0.522	3.429
run035	6.0	**124.21**	-8.20	1.55	2.76	167.30	-4.52	76.69	76.76	**130.85**	**-1.76**	-0.406	3.741
run036	7.0	**130.69**	-8.69	2.00	3.85	176.31	-4.82	76.69	76.75	**152.93**	**-1.04**	-0.191	4.370
configuration 1 - TI = 1.3%													
zero04		0.4	0.4	0.4	0.0	0.0	-0.1	0.0	-0.1	-0.47	-0.05	0.00	-0.01
run037	0.0	**39.87**	-2.66	0.41	1.75	47.76	-1.31	76.73	76.80	**-0.48**	**-0.64**	-0.161	-0.008
run038	1.0	**49.43**	-1.50	0.67	-0.24	61.45	-1.83	76.73	76.79	**21.61**	**-0.73**	-0.146	0.622
run039	2.0	**74.16**	-2.21	0.90	-1.19	96.79	-2.78	76.73	76.79	**43.71**	**-1.65**	-0.382	1.253
run040	2.5	**86.14**	-3.06	0.93	-1.53	113.85	-3.14	76.71	76.79	**54.48**	**-2.69**	-0.647	1.560
run041	3.0	**104.66**	-3.54	1.33	-4.54	140.09	-3.92	76.72	76.80	**65.44**	**-5.79**	-1.468	1.871
run042	3.5	**120.88**	-4.18	1.58	-4.28	163.43	-4.57	76.71	76.78	**76.21**	**-5.82**	-1.503	2.180
run043	4.0	**131.23**	-4.93	1.52	-3.15	178.01	-4.84	76.71	76.78	**87.01**	**-5.21**	-1.350	2.489

run044	4.5	**137.59**	-5.41	1.40	-2.08	186.84	-5.13	76.71	76.78	**98.20**	**-4.52**	-1.172	2.809
run045	5.0	**142.69**	-5.78	1.27	-1.19	194.03	-5.23	76.71	76.78	**109.24**	**-3.82**	-0.986	3.123
run046	5.5	**147.24**	-6.15	1.29	-0.35	200.35	-5.23	76.71	76.78	**119.99**	**-3.25**	-0.832	3.430
run047	6.0	**150.96**	-6.62	1.21	0.56	205.62	-5.32	76.71	76.77	**130.96**	**-2.71**	-0.683	3.743
run048	7.0	**155.69**	-7.26	1.22	2.06	212.21	-5.35	76.71	76.77	**152.93**	**-1.82**	-0.428	4.371
configuration 2 - TI = 1.3%													
zero05		0.2	0.0	0.2	0.1	0.2	-0.3	0.0	-0.1	-0.45	-0.06	0.00	-0.01
run049	0.0	**38.51**	-2.19	0.87	0.74	46.56	-1.66	76.96	77.04	**-0.48**	**-0.68**	-0.147	-0.008
run050	1.0	**47.35**	-1.88	-0.02	-0.16	58.91	-2.53	76.95	77.03	**21.51**	**-0.70**	-0.137	0.619
run051	2.0	**70.66**	-2.78	0.47	-1.02	92.55	-3.60	76.95	77.02	**43.69**	**-1.68**	-0.386	1.251
run052	2.5	**83.32**	-2.51	0.46	-3.18	110.67	-4.45	76.94	77.02	**54.47**	**-2.89**	-0.703	1.560
run053	3.0	**99.71**	-3.75	-1.29	-4.64	133.54	-5.34	76.94	77.01	**65.35**	**-5.21**	-1.316	1.870
run054	3.5	**115.36**	-5.11	-0.94	-3.57	155.67	-6.28	76.94	77.01	**76.16**	**-5.23**	-1.346	2.181
run055	4.0	**124.59**	-6.32	-0.41	-1.91	168.61	-6.71	76.94	77.01	**87.06**	**-4.61**	-1.191	2.491
run056	4.5	**130.28**	-6.92	0.00	-0.78	176.46	-7.02	76.93	77.01	**98.28**	**-3.90**	-1.002	2.811
run057	5.0	**135.56**	-7.76	0.37	0.48	183.93	-7.17	76.93	77.00	**109.17**	**-3.42**	-0.875	3.122
run058	5.5	**139.54**	-8.27	0.62	1.45	189.74	-7.12	76.93	77.00	**120.00**	**-2.89**	-0.732	3.430
run059	6.0	**142.89**	-8.80	0.70	2.45	194.31	-7.13	76.93	77.01	**130.91**	**-2.44**	-0.608	3.743
run060	7.0	**148.57**	-10.08	1.13	4.50	202.47	-7.01	76.93	77.00	**152.98**	**-1.58**	-0.359	4.372
configuration 3 - TI = 1.3%													
zero06		0.0	0.1	0.0	0.1	0.1	-0.3	0.0	-0.1	-0.47	-0.05	0.00	-0.01
run061	0.0	**30.03**	-0.57	0.42	-0.63	35.07	-1.83	76.70	76.77	**-0.48**	**-0.48**	-0.108	-0.008
run062	1.0	**40.08**	-0.80	-0.78	-1.20	49.57	-2.69	76.71	76.78	**21.52**	**-0.67**	-0.120	0.620
run063	2.0	**60.30**	-0.46	-0.76	-3.87	79.00	-4.43	76.62	76.70	**43.60**	**-1.94**	-0.440	1.249
run064	2.5	**71.48**	-1.29	-3.21	-4.53	94.09	-5.46	76.62	76.69	**54.52**	**-3.29**	-0.792	1.561
run065	3.0	**81.81**	-3.19	-4.40	-2.91	108.11	-6.32	76.61	76.68	**65.27**	**-3.68**	-0.915	1.869
run066	3.5	**91.07**	-4.71	-3.97	-1.07	121.18	-7.31	76.62	76.67	**76.18**	**-3.37**	-0.836	2.180

run067	4.0	**96.91**	-5.61	-3.31	0.32	129.36	-7.86	76.61	76.68	**87.10**	**-2.71**	-0.658	2.491
run068	4.5	**102.00**	-6.23	-2.66	1.30	136.60	-8.30	76.61	76.68	**98.29**	**-2.33**	-0.561	2.811
run069	5.0	**105.31**	-6.77	-2.00	2.35	141.39	-8.52	76.61	76.67	**109.11**	**-1.98**	-0.471	3.121
run070	5.5	**109.55**	-7.57	-1.69	3.41	147.53	-8.69	76.61	76.67	**119.85**	**-1.67**	-0.388	3.428
run071	6.0	**111.22**	-8.16	-1.42	4.53	149.86	-8.85	76.61	76.67	**130.80**	**-1.28**	-0.281	3.740
run072	7.0	**116.55**	-9.48	-0.74	6.69	157.40	-8.81	76.60	76.67	**152.96**	**-0.63**	-0.081	4.371