Experimental study to determine flow characteristic effects on marine current turbine behaviour

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Abstract

This paper presents experimental results from tests carried out in the Ifremer free surface circulation flume tank. The objective of this work is to validate the numerical work conducted under a PhD programme for the characterization of flow perturbations induced by marine current turbines. For that purpose, we used a tri-bladed horizontal axis turbine. The work is dedicated to measure the behaviour of the system and to characterize the wake emitted by the turbine. The efficiency of the turbine is quantified by the measurement of the thrust and the amount of power generated by the rotor for various inflow conditions, while the wake will be characterized by Laser Doppler Velocimetry.

Particular attention is paid to the flow characteristic effects (velocity gradient, flow orientation, etc) on the performance of a 0.70 m diameter turbine. The load predictions on the structure and the measured performance of the turbine over its working range of currents (0.6 to 1.5 m/s) and rotational speed is within 5% of TGL's analytical model. The trials showed that this kind of turbine is sensitive to the quality of the incoming flow and a misalignment of a fixed turbine can cause significant losses. The turbulence intensity effects on turbine behaviour are also characterized in this paper.

Keywords: Hydrodynamic, marine energy, experimental trials, flume tank, numerical simulations, marine current turbine, turbulence effects.

Introduction

The future deployment of marine current energy converters raises questions about their impact on the flow, the interactions with the free surface and the seabed [1], [2]. The question is a timely one, as the first large-scale devices have been installed within the past few years (for example the Marine Current Turbines 1.2MW 'Sea-Gen' device situated in Strangford Lough, Northern Ireland). In order to quantify these phenomena, Ifremer has started is developing numerical tools under a PhD programme to help with the impact assessment on the flow of future commercial installations.

Software capable of three-dimensional flow modelling, taking into account the non stationary evolution of the wake emitted by a tri-bladed horizontal axis turbine has been developed in order to assess the disturbances generated on its close environment. Currently, we are able to simulate the behaviour of one turbine and to determine the characteristics of the emitted wake [3]. The dynamics of farms consisting of numerous devices placed in close space will also be analysed. These numerical tools will be used prior to the installation of a marine current turbine farm, with the aim of quantifying the interactions with the immediate environment.

In order to validate this numerical work, experimental trials were carried out in the Ifremer free surface circulation flume tank. This work is dedicated to measure the behaviour of a tri-bladed horizontal axis turbine and to characterize the wake emitted by its rotor. The efficiency of the turbine will be quantified by the measurement of the thrust and the amount of power generated by the rotor for various inflow conditions, while the wake will be characterized by Laser Doppler Velocimetry.

Capturing the spatial and temporal variation in the marine flow is vital for the prediction of both performance and loading on marine current turbines. Particular attention is therefore paid to the flow characteristic effects (homogeneous flow, flow with a velocity gradient, flow orientation) on the performances of the turbine and the loading and electrical performance results under each of these conditions were compared. We also focus our work on the characterization of the turbulence intensity effects on the performances of the turbine. For that purpose we consider two levels of turbulence intensity: 8% and close to 25%. Comparisons between numerical and experimental results are still in progress and will be presented in the near future.

1 Materials / Methods

The turbine used for these trials was developed by TGL (Tidal Generation Limited [4]) before the design of a 500kW, fully submerged tidal turbine prototype, designed for deep water generation. In order to conduct our work at a representative scale and without blockage effects [5], trials were carried out in 2007 on a 1/30th scale model mounted on a 6-component load cell in a *free hinge downstream* configuration. This configuration is shown on Fig. 1. The tri-bladed rotor was connected to a motor-gearbox assembly capable to provide active rotor speed control (gearbox, DC motor, ballast load, motor speed control unit).

The pitch of the three blades was adjustable. The diameter of the tested rotor was 0.6 m, which created a blockage ratio (percentage of cross section occupied by the rotor) of approximately 4%. The model was tested at speeds ranging from 0.5 to 1.5 m/s and the turbine performances obtained over a range of rotor speed from 10 to 190 rpm and blades pitch angle from –5 to 15 degrees. The results have been presented in [6].

As intended, the rotor assumed a substantially horizontal orientation when generating (Fig. 1). However, although the free hinge downstream testing showed that the turbine was dynamically stable in this configuration across the full range of current and rotational speeds, TGL decided to stop the development of this concept to focus their work on an upstream horizontal axis concept. With this new design, TGL aims to reduce blade loading and achieve better dynamic behaviour.

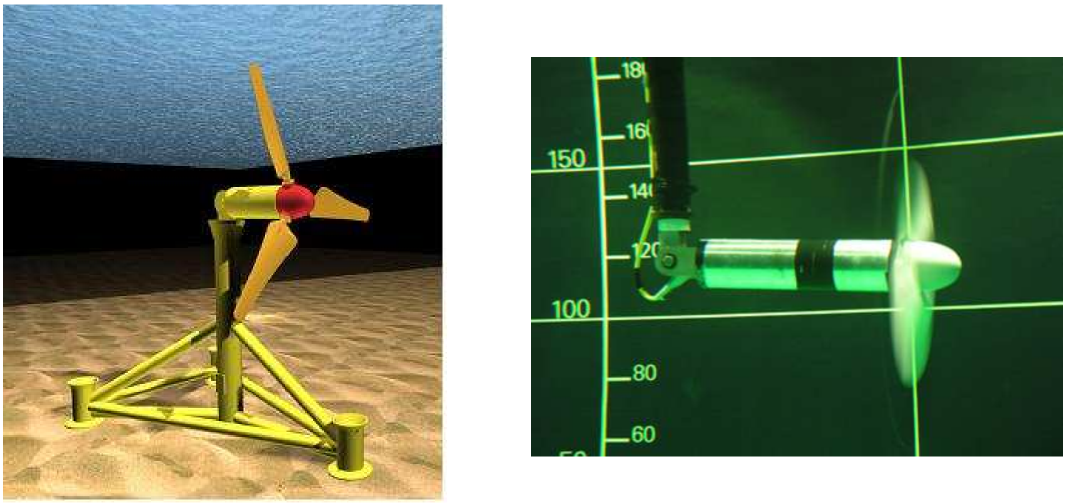

Figure 1: Fully submerged turbine initially developed by TGL and free hinge configuration at optimal speed

For this reason (modification of the TGL concept, Fig. 2, and PhD work at Ifremer) it was decided to collaboration on a second set of trials. For these tests, a new 700 mm diameter (D) tri-bladed horizontal axis turbine is used in order to validate some blade shape improvements (confidential), but also in order to:

- determine the effects of changing flow characteristics (homogeneous flow, flow with a velocity gradient, flow orientation, turbulence intensity) on the operational loads with a 6-component load cells

- characterise the wake of the turbine for different flow conditions (incidence, turbulence intensity, turbine location) with a 2D laser doppler velocimeter

- load measurements on an instrumented blade with the use of strain gauges.

To date, all of these tests are still in progress and only the first one is partially completed and presented in this paper. The flow measurements will be carried out in June 2009, while blade deformations will be investigated during the summer 2009. Indeed, initial analysis has shown that the strains on the blades should be measurable. Data will be collected using an autonomous data logger installed in the nose cone of the model.

Experimental campaigns carried out for this project are performed in the Ifremer (French Research Institute for Exploitation of the Sea) free surface hydrodynamic water tunnel, Fig.3. The flume tank is 18 m long by 4 m wide and 2 m deep with a side observation window of 8 m x 2 m (this large window placed on one side of the tunnel allows users to observe the behaviour of the models during trials and to carry out video sequences).

The channel is a closed loop system with 2 large variable-speed axial flow pumps providing the thrust to circulate the water with a flow velocity range of 0.1 to 2.2 m/s. With the use of honeycomb flow straighteners, the flow turbulence is of the order of 8%. Without these flow straighteners the flow turbulence can reach 25%.

The following instrumentation developed for force, velocity and wave measurements is available:

- 3 and 6 components load cells with a upper limit of 1500 N for forces and 1000 N for moment measurements

- two non-intrusive optical measurement devices for flow characterisation: a two components Laser Doppler Velocimetry system (LDV) for local measurement and a two components Particle Image Velocimetry system (PIV) for global information on the water flow.

The LDV system accurately measures the mean and fluctuating components of fluid velocity. Despite the low data rate obtained in some of the zones being investigated, the data sets allow us to calculate turbulence parameters. The water is seeded with 15 micron diameter polyamide seeding particles and the flow velocity can be measured along vertical and/or horizontal profiles. Classical measured velocity components are: the axial component (along the x axis) and the tangential component (along y axis). This allows us to obtain the flow characteristics all around the majority of the studied devices. The third component (along the z axis) can be measured in a second time with the utilization of a 90° transmitter probe. All this would be possible by the use of a 3 axis traverse system to move the light source with an accuracy smaller than 0.1mm.

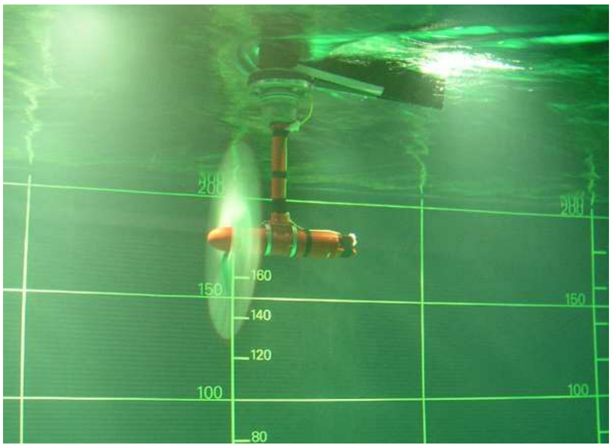

Figure 2: Fully submerged turbine now developed by TGL and model turbine during trials in the Ifremer tank

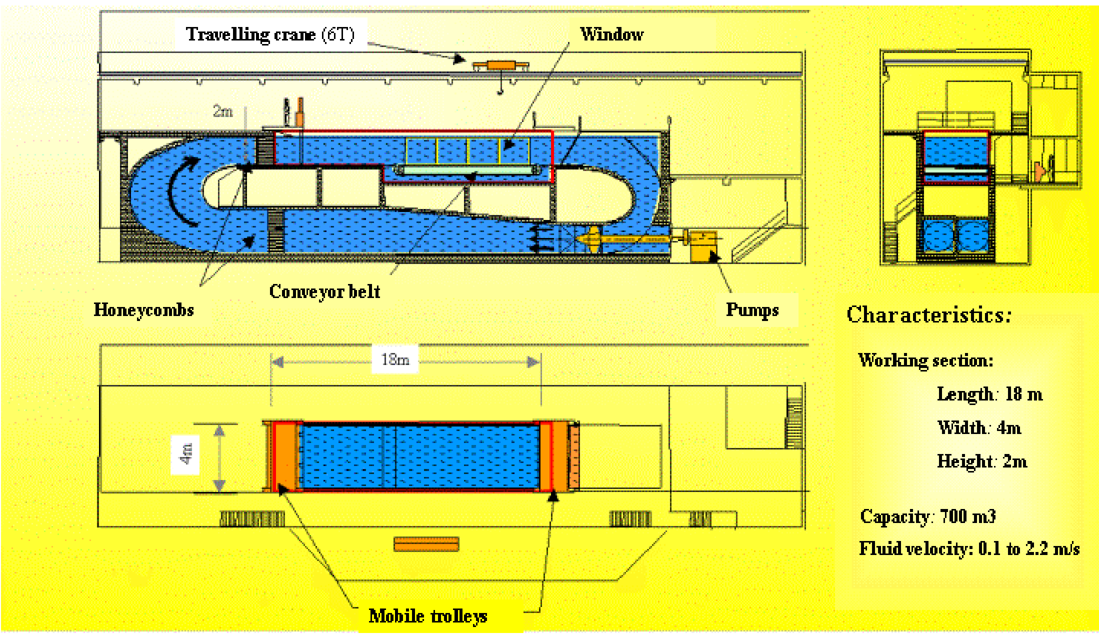

Figure 3: Ifremer free surface hydrodynamic water tunnel located in Boulogne-sur-Mer, France.

A particular feature of the LDV measurements is that the amount of data recorded in a given time window is strongly dependent on the local seeding conditions [6]: measurements are possible only when a particle is moving across the probe volume. So the data rate is generally of the order of 50 Hz.

In order to achieve samples of data as homogeneous as possible, an inhibit method can be used and data recorded under time rather than sample length control. This technique allows us to obtain a sample length of the order of 100 seconds (that is an order of magnitude for the time window larger than the time scale of the flow fluctuations) with a number of data per sample of the order of few thousand. The long time interval allows an accurate estimate of average values, both for velocity and turbulence intensity.

The LDV system is regularly used to determine and to verify the quality of the flow in the tank. Fig. 4 gives the dispersion of the axial velocity around a mean axial velocity value of 0.79 m/s for an homogeneous flow in the central part of the tank (i.e. axial velocity variation of less than 2% between the positions y = ±500mm), a flow with a transverse speed gradient of 8% (left to right gradient between the positions y = ±500mm) and a flow with a turbulence intensity rate of 25%, calculated according to the following equation:

$$TI = 100 \times \frac{\sqrt{(\sigma u)^2 + (\sigma v)^2 + (\sigma w)^2}}{\sqrt{u^2 + v^2 + w^2}}$$

giving a relative measure for turbulence (σ indicates standard deviation). This kind of velocity map will also be used to characterize the wake of the turbine in order to evaluate the flow perturbation and to develop a data-base for numerical validations. During trials, the time history data of the flow speed at the centre of the tank was recorded and synchronized with, for example, power measurements in order to characterize precisely the response of the system.

From these data, it is also possible to quantify the power in the flow available to the turbine and to determine its performance. The available power at mid-depth location for the three kinds of tested flow is 92W for the homogeneous flow (config. 1), 104W for the left to right velocity gradient flow (config. 2) and 78W for the flow with a turbulence intensity rate of ~25% (config. 3). The available power for the two other tested locations with an homogeneous flow is also close to 92W for the 0.94D and 2.04D turbine locations (the position 1.5D corresponding to a mid-depth location in the tank).

2 Results

In order to protect the confidentiality of these data, all the following results will be presented as raw outputs from the measurement system (i.e. they will not be transformed into real coefficients or values). The objective here is merely to give some comparisons between configurations and to determine some possible effects on the turbine behaviour. To this aim, the data will be all non-dimensionalized and given in function of a normalised Tip Speed Ratio: $TSR^* = \frac{\Omega D}{2U_\infty} \times A$, with the coefficient A not given here.

In order to study the impact varying flow characteristics can have on a tri-bladed horizontal axis turbine, the performance of the turbine over a range of common rotor speed (of the order of few tens of rpm) and a range of mean flow speed between 0.3 to 1 m/s was measured for:

- three kinds of flow: an homogeneous one, a flow with a transverse velocity gradient and a flow with an intermediate turbulence intensity rate

- three locations in the tank: turbine axis position located at 0.94D, 1.57D and 2.04D from the free surface.

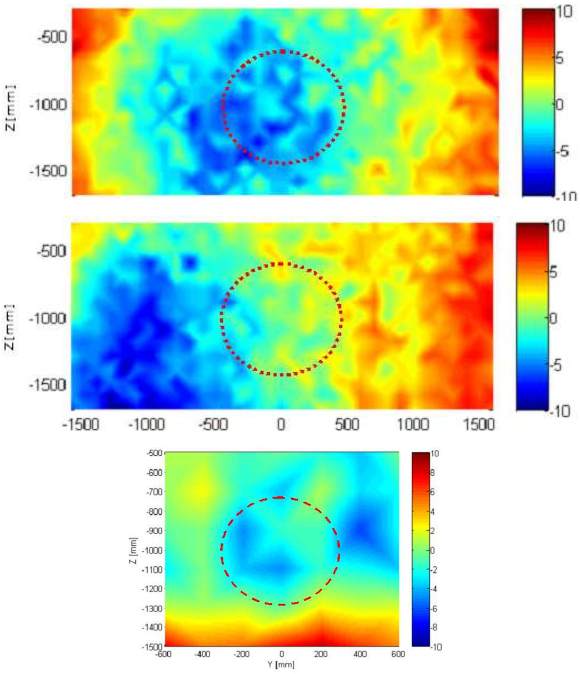

Figure 4: Maps of the flow with a mean speed of 0.79m/s for the three kinds of tested flow: homogeneous flow at the top, flow with transverse gradient of 8% at the middle and a flow with a turbulence intensity rate of ~25% at the bottom

First of all, from these results we can validate the mathematical results obtained by TGL from a model based on the blade element momentum (BEM) theory. This theory is based on a combination of momentum and blade element theories for predicting the performance of the turbine and the blade loadings. Comparisons give:

a/ the measured performance of the turbine over its working range of current (0.6 to 1.5 m/s) and rotational speed is within 5% of TGL's analytical model predictions

b/ the load predictions on the structure are also within 5% of model predictions (see Fig. 5).

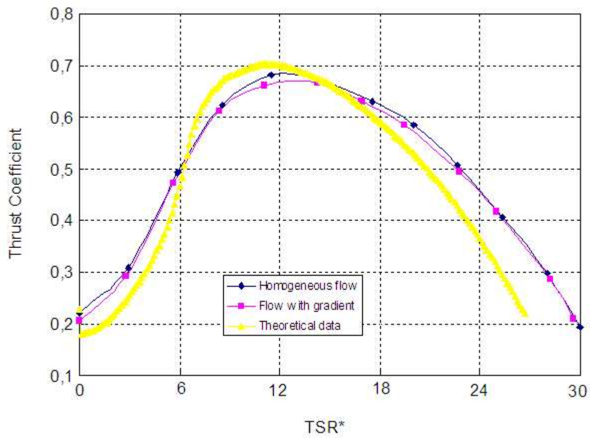

Figure 5: Thrust coefficient comparison (theoretical and experimental data) at a mean speed of 0.79 m/s

Figure 6 shows the measured power needed to ensure the specific constant rotational speed of the turbine for both an homogeneous flow and a flow with a transverse gradient of 8%. The power values given here take into account the losses in the gearbox and the inefficiencies of the motor itself. Results show a similar response of the turbine for both configurations. Unfortunately, the theoretical available power difference between both configurations reaches 10%. This difference is surprisingly not visible on the measured power given here. If we can't quantify here the loss of power, it is evident from these results that this kind of system is less efficient when it is in presence of non homogeneous flow.

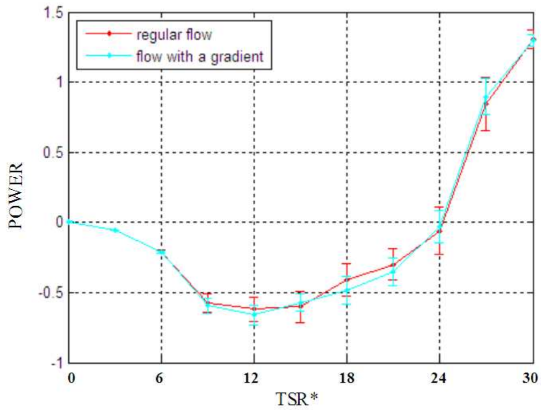

Figure 6: Measured power for an homogeneous flow and a flow with a gradient

No more sensitive effects can be seen in Fig. 7, where we present the thrust (RMS values, measured with a six components load cells) on the 3 blades for each configurations, even if the thrust fluctuations are always lower for the flow with a gradient than for the homogeneous one (certainly due to the higher flow speed). Some characteristics of the wake emitted by the turbine in these different configurations should give additional information in order to try to understand these phenomena, both for the kind of flow or location of the turbine in the tank.

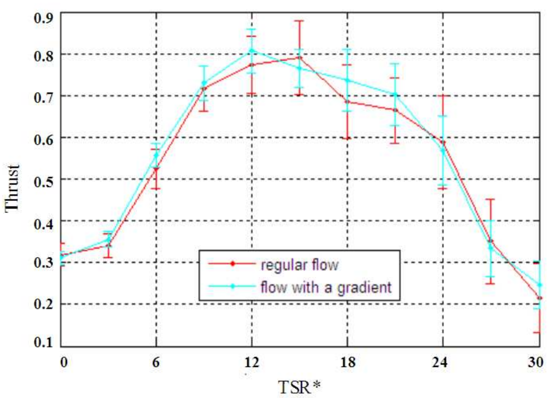

Figure 7: Normalised thrust for an homogeneous flow and a flow with a left to right gradient

Moreover, a similar response is obtained from the comparison between depth locations, but from the results given in [7] we might think the opposite. The theoretical extracted available power is equivalent for the three locations. If there are some effects on the emitted wake, it seems not to affect the behaviour and performance of the turbine. During the next experimental campaign we will increase the flow gradient in order to improve these results and to determine the value from where significant changes occur. These new configurations will be obtained with a location of the turbine close to the bottom of the tank (in the boundary layer). Like this, we will be able to reproduce a decrease of 20% of the flow velocity across the blades.

In order to complete the analysis of the force measurements, we present Fig. 8 the axial forces spectrum for four rotor speeds and five turbine orientation angles (between –10 to 20 degrees), the turbine located at mid depth. These results do not show any significant differences between the different orientation angles, but they give the natural frequency of the system (first peak) and the response of the turbine (second peak) and his harmonics for each TSR*. The maximal response (energy level) is obtained here when the maximum performance is achieved. At both sides of this point (at lower and higher tip speed ratio), the harmonics become more present.

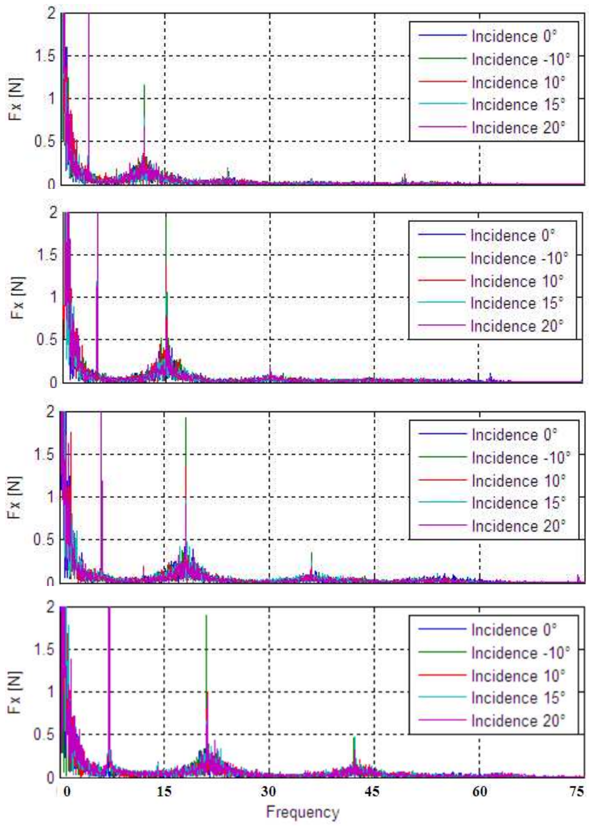

Figure 8: Axial forces spectrum for four rotor speeds for five orientation angles of the turbine in the flow between –10 to 20 degrees (increasing TSR from the top to the bottom)

Fig. 10 shows the thrust variations as a function of TSR* for five orientations of the turbine in the flow (Fig. 9). These configurations were tested in order to characterise the effects of a misalignment during installation but also the effects of variations of the flow direction during the reverse of the flow or during a tide cycle. From this graph, we can see some small effects for a variation of ±10°. For orientation higher than 10°, the thrust losses are significant: of the order of 15%.

The torque imposed by the rotor on the turbine is shown in Fig. 11. The variations as a function of the alignment of the turbine correspond more closely to what was expected: a decrease in torque with the reduction of the quantity of flow shown by the blades and the attachment or not of the flow on the blades. The loads on the blades present a significant gap between the orientations –10 and 10 degrees, while the thrust seems to be not influenced by the incidence of the flow.

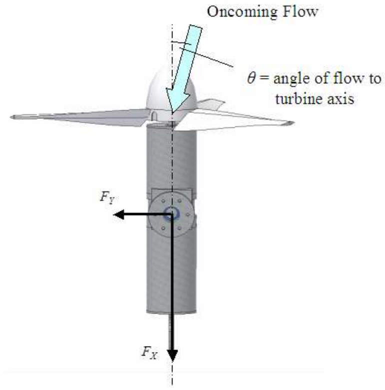

Figure 9: Scheme of the turbine orientation in the tank

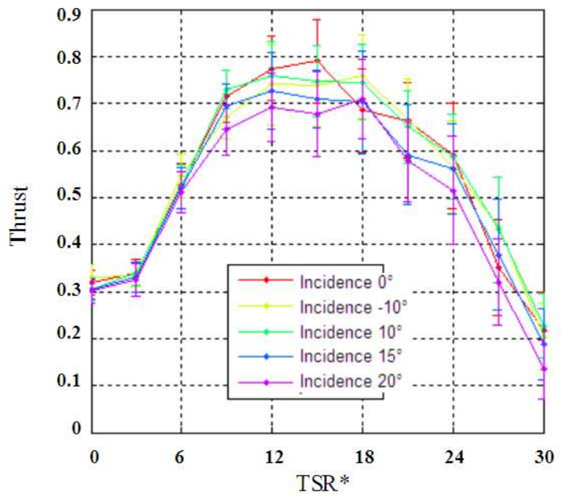

Figure 10: Normalised thrust for several turbine orientations at a mid-depth location

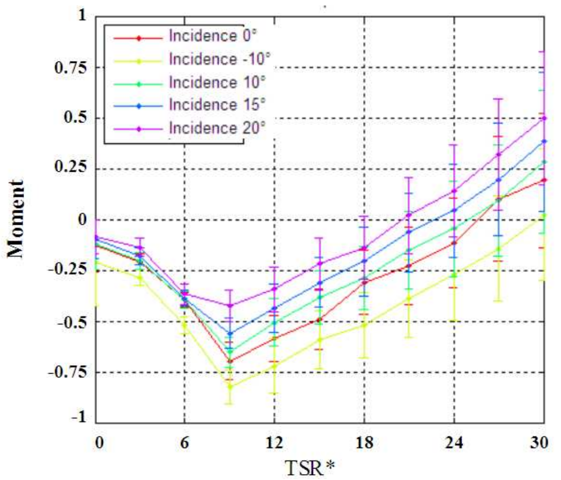

Figure 11: Normalised rotor torque for several turbine orientations at a mid-depth location

Fig. 12 shows the measured power needed to ensure the specific constant rotational speed of the turbine for the five turbine alignment angles investigated. A misalignment of -10° of the turbine can cause significant losses while a misalignment of 10° seems to be not significant. The effective angle of incidence of the flow on the blades is not altered in the same way by the orientation of the turbine. It can be seen clearly in this figure that the thrust drops as the angle of yaw increases.

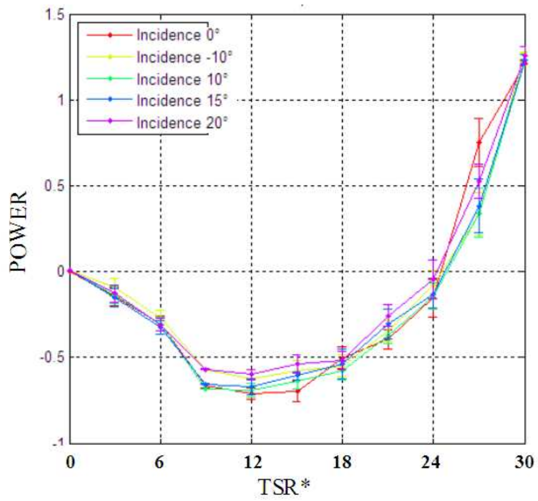

Figure 12: Measured power for several turbine orientations at a mid-depth location

During these trials, we have also focussed our future work on the characterization of the turbulence intensity effects on the performances of the turbine. For that purpose we have considered two levels of turbulence intensity rates: close to 8% and close to 25%. As we can see from Fig. 13, the behaviour of the turbine is the same for both kinds of flow. As expected, the thrust fluctuations are always higher for the high turbulence rate than for the smaller one: double for the 25% turbulence intensity rate compared to the 8% one. If, like shown in [8], the force oscillations are three times greater than the force oscillations for the three blades (as given here) due to the level of velocity fluctuation it could be a useful determinant for the fatigue loading on the structure.

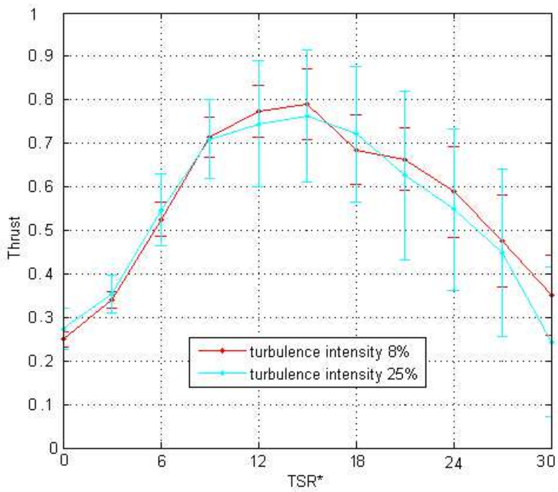

Figure 13: Normalised thrust for turbulence intensity levels of 8% and 25% at a mid-depth location

Fig. 14 shows the axial forces spectrum for the two turbulence intensity rates (as before, the turbine is located at mid depth). These results highlight the high level of the loading fluctuations on the structure.

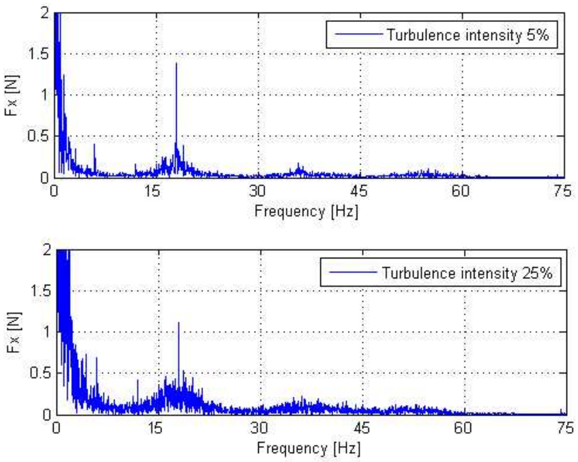

Figure 14: Axial forces spectrum for two turbulence intensity levels, *i.e.* 8% and 25%

The available power for the flow with a turbulence intensity rate of 25% is 15% lower than that of the reference flow. If we compare the power needed to ensure the constant rotational speed of the turbine for both intensity rates (given Fig. 15), we find a difference of less power than expected: 9% compared to the previous 15%.

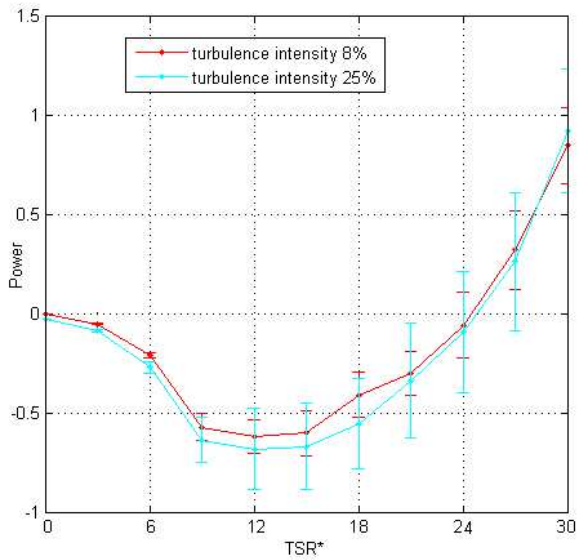

Figure 15: Measured power for both turbulence intensity rates of 8% and 25% at a mid-depth location

Conclusion

Successful measuring of the performance characteristics of a tri-bladed horizontal axis turbine have been conducted in a free surface circulation tank. A specific assembly has been designed and a test programme carried out which provided good results and suitable data for validating theoretical and numerical methods. The results provided here correspond to those obtained from the mathematical model developed by TGL on both performance and loads.

Two power control strategies were also tested to investigate the sensitivity of the turbine power output to natural turbulent fluctuations in the flow. Again close correlation was achieved with TGL's analytical model. Important data was gathered to inform the design of the control system for the large scale 500kW machine that TGL is developing, allowing fluctuations in rotor torque and power to be minimised.

More academic trials showed that this kind of turbine is not sensitive to the quality of the incoming flow, but a misalignment of a fixed turbine can cause a significant loss of power. The characterization of the turbulence effects on the behaviour of the turbine should be extended in order to evaluate the impact that the high loading fluctuations on the blades could have on the fatigue of the structure. Further development should also be carried out to simulate more realistic sea states (wave effects), as in [9]. Combined trials with waves and current will be carried out in the Ifremer flume tank in 2010.

This work will shortly be completed by flow measurements for wake effects characterization. The blade deformations will also be characterized in order to quantify flow effects on the fatigue of the structure. For this purpose, an autonomous data logger will be installed in the nose cone of the model and the blade strains will be measured with the use of strain-gauges. Comparisons between numerical and experimental results should be obtained in the near future.

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