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Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: One single turbine

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ABSTRACT

The ambient turbulence intensity in the upstream flow plays a decisive role in the behaviour of horizontal axis marine current turbines.

Experimental trials, run in the IFREMER flume tank in Boulogne-Sur-Mer (France) for two different turbulence intensity rates, namely 3% and 15%, are presented. They show, for the studied turbine configuration, that while the wake of the turbine is deeply influenced by the ambient turbulence conditions, its mean performances turn out to be slightly modified.

The presented conclusions are crucial in the view of implanting second generation turbines arrays. In addition, complete and detailed data sets (wake profiles and performance graphs) are made available to the scientific community in order to encourage further comparisons.

1. Introduction

The ambient turbulence intensity in the upstream flow plays a decisive role in the behaviour of horizontal axis marine current turbines. First, turbulence intensity may influence the turbine performances but, probably most important, it deeply influences the wake shape. This last issue is of crucial matter for the onset of marine current turbine arrays. Indeed, in second generation arrays, the wake of an upstream turbine may irreparably affect the power performances of another turbine positioned downstream. This aspect of elementary interactions between marine current turbines in an array will be treated in the second part of this study [1]. The present paper aims at characterising precisely the performances and wake of a single turbine depending on the ambient turbulence intensity of the incoming flow. The results of this first part will represent a strong basis for comparisons with the twin turbines setups investigated in the second part.

Several *in situ* studies were carried out to characterise the turbulence intensity in potential sites, where marine current turbines are expected to be installed. These studies are extremely difficult to undertake owing to their important cost, the possible harsh metocean conditions encountered, as well as the high quality measurement devices that are required to assess the turbulence intensity. Most of the studies focused on a streamwise turbulence intensity $I_\infty^{1D} = \sigma_u/U_\infty$. In order to obtain a 3D turbulence intensity rate I_∞, Milne et al. [2] precisely measured the anisotropic ratio (σ_u:σ_v:σ_w)=(1:0.75:0.56) in the Sound of Islay (Scotland, UK); and found it similar to the values given by Nezu et Nakagawa [3]. Table 1 summarises the *in situ* flow measurements mentioned in the sequel. In order to obtain 3D I_∞ values from the I_∞^{1D} given in all other studies, the precise (σ_u:σ_v:σ_w)=(1:0.75:0.56) anisotropic ratio from [2] was assumed.

Among the last studies, Osalusi et al. [4,5] used an Acoustic Doppler Current Profiler (ADCP) to assess several turbulence characteristics such as Turbulent Kinetic Energy production and dissipation, Reynolds shear stresses, etc. Their study was carried out in the Fall of Warness (Orkney Islands, Scotland, UK) during a week, precisely at the tidal test site of the European Marine Energy Centre (EMEC). Following the previous assumption, the 3D turbulence intensity lies between $I_\infty \approx 7.9$–8.7% at 5 m from the seabed for a mean velocity of 1.5 m s^{-1}. In their *in situ* study, Milne et al. found a 3D turbulence intensity I_∞ of approximately 9.5–10.3%, depending on flood and ebb tides. The measurements [2] were performed in the Sound of Islay (Scotland, UK) at 5 m from the seabed for a mean velocity of 2.0 m s^{-1}. They lasted approximately

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Table 1
In situ measurements of turbulence intensity rates I_∞ in the literature. I_∞^{1D} stands for the streamwise turbulence intensity rate, I_∞ the 3D turbulence intensity rate, U_∞ the mean velocity, z_m the vertical distance to the seabed. Except for the study of Milne et al. [2], where the anisotropic ratio (σ_u:σ_v:σ_w)=(1:0.75:0.56) was measured, this precise ratio was assumed for all the other studies, so as to deduce 3D I_∞ values.

Location	I_∞^{1D} [%]	I_∞ [%]	U_∞ [m/s]	z_m [m]	Techniques	Ref
Fall of Warness	10 − 11	7.9 − 8.7	1.5	5.0	ADCP	[4,5]
Sound of Islay	12 − 13	9.5 − 10.3	2.0	5.0	ADV	[2]
Puget Sound	8.4/11.4	6.6/9.0	1.3 (±0.5)	4.7	ADV/ADCP	[6]
Strangford Narrows	4 − 9	3.2 − 7.1	1.5 − 3.5	14	–	[7]
East River, NY	20 − 30	16 − 24	1.5 − 2.3	5.22	ADCP	[8]

15 days and used a 4 Hz ADV (Acoustic Doppler Velocimeter). Thomson et al. [6] carried out a similar study comparing two measurement techniques, ADCP and ADV, at 4.7 m from the seabed in the Puget Sound (Washington State, US). They clearly indentified several sources of error while measuring turbulence intensities with ADCP, and precisely quantified them. ADCP and AVD techniques respectively gave a streamwise turbulent intensity of $I_\infty^{1D} = 8.4\%$ and $I_\infty^{1D} = 11.4\%$ at the same point (the Nodule Point, Puget Sound), even with Doppler noise correction for the ADCP measurements. It should be mentioned that although ADCPs are commonly used to evaluate turbulence, potential errors can be made, essentially due to the compromise made between accuracy and resolution. Errors may also issue from the hypothesis made on the steadiness and horizontal uniformity of the turbulence, which are in contradiction with the highly intermittent and multi-scale feature of the phenomenon [9,10].

The streamwise turbulence intensities from the three previous studies [2,4–6] are very similar in order of magnitude, ranging from approximately 8.4% to 13%. However, the turbulence intensity I_∞ does not seem to be a global constant, or even a geographical site constant. As a matter of fact, in a recent paper, Mac Enri et al. [7] indicate that the 3D turbulence intensity I_∞ may vary from approximately 3.2% to 7.1% depending on the mean velocity, ebb and flood or neap and spring tides. At a given point, the turbulence intensity may vary significantly depending on time varying tidal physical values. Their measurements were carried out in the Strangford Narrows (Republic of Ireland), where the 1.2 MW SeaGen marine current turbine is installed. The measurements were performed at the hub level, *i.e.* 14 m from the seabed, with an electromagnetic current meter (Valeport Model 803) with a 1 Hz frequency. Their velocity measurements were also calibrated with an ADCP.

Spatial variations may also occur in a given geographical site. The study by Gooch et al. [11] gave varying turbulent intensity rates depending on the precise location in the Puget Sound. In fact, five locations in the Puget Sound were assessed: Admiralty Inlet, North East off the Marrowstone Lighthouse and three locations East the Marrowstone Island at the smallest cross-sectional area of the Puget Sound. The measurements, from one to two months (between 33 and 75 days), were obtained with ADCP. Small variations between ebb and flood tides were observed. However, the streamwise turbulent intensities obtained were ranging from $I_\infty^{1D} \approx 2.8$ to about 5.4% at several locations and several depths within the Puget Sound. Taking the latest results by Thomson et al. [6] into account, for a single geographical site, the streamwise turbulence intensity ratio I_∞^{1D} range lies between about 2.8% and 11.8% at different locations and different depths. Even if the turbulence intensity increases with the depth [6], these variations are however important within a single geographical site. Finally, the study by Li et al. [8] in the East River (New York, NY) gave an estimated $I_\infty \approx 16–24\%$ provided that the (σ_u:σ_v:σ_w) assumed ratio is still valid in the case of a river. Still, their measurements of streamwise turbulence intensity rate $I_\infty^{1D} = 20 - 30\%$ are noticeably higher than the previous ones from Table 1.

The flume tank experiments presented in this paper were carried out in incoming flows with two precise turbulence intensity rates, namely $I_\infty = 3\%$ and $I_\infty = 15\%$. These two values are actually representative of the I_∞ range depicted in Table 1, with the minimum values of $I_\infty \approx 3.2\%$ in the Strangford Narrows [7] to the higher values of Li et al. [8] in the East River ($I_\infty \gtrsim 15\%$). For the given turbine geometry used in this study, the present paper aims at describing major differences in the performances and wake characteristics between I_∞=3% and 15%.

Experimental trials on a single marine current turbine in a flume tank have already been carried out, using different techniques. Bahaj et al. [12,13] carried out a power (C_P) and thrust (C_T) coefficient study on a 0.8 m-diameter turbine model in a towing tank and in a cavitation tunnel. However, in the previous two studies, the wake behind the turbine was not characterised. On the other hand, experimental wake characterisation is available in Refs. [14,15] under an actuator disc approximation. Unfortunately, this approximation does not take intrinsically into account the fluid rotation in the wake, and the power and thrust assessment is more complex. Rose et al. [16] performed several experimental trials, some in a flume tank and others in open water (Montgomery Lough) using either PIV (Particle Image Velocimetry) or ADV (Acoustic Doppler Velocimeter) techniques. Several turbines were tested, the biggest one being a 1/10th scale turbine model of 1.5 m in diameter in the lake (Montgomery Lough). However, only wake velocity measurements are presented in the paper without any turbine performance. Stallard et al. [17] also give interesting information on a single turbine wake, including turbulence intensity, even if their study mainly deals with turbine interactions. For Tedds et al. [18], many turbine performance curves are depicted depending on the number of blades, pitch angles, etc. but without much details about the wake velocity profiles. In another study, Milne et al. [19] gave interesting turbine performance and thrust curves even though their study was mainly oriented towards blade loads owing to oscillatory flows, similarly to Davies et al. [20].

The present study aims at characterising both the power and thrust coefficient curves (C_P and C_T curves) together with detailed wake profiles including turbulence intensities. This paper follows the same experimental procedures as presented in Ref. [21], but with an open-modified version of the turbine which enables the diffusion of the blades geometry. Some of the experimental results were partially presented or used as a matter of numerical-experimental validation in Refs. [22,23]. The present document presents all our latest experimental results of a single 3-bladed turbine immersed in two different turbulence intensities, namely $I_\infty = 3\%$ and $I_\infty = 15\%$.

First of all, Section 2 details the experimental setup, measurement techniques and turbine geometry. Section 3 presents the power and thrust coefficient curves, for different incoming mean velocities and the two turbulence intensity rates. The standard deviations of these curves are also shown. Then, Section 4 gives streamwise velocity, turbulence intensity and Reynolds shear stress maps depending on the two turbulence intensity rates. The wake is also characterised using integrated quantities. Finally, most of the raw results are made available in the appendices as a matter of validation with future numerical studies. This intends to answer to a recurrent request, the latest being by Churchfield et al. [24].

2. Experiments description

This section aims at giving a detailed description of the experimental setup and measurement facilities used for the experiments.