Empirical Far Wake Model of a Seabed-Mounted Tidal Turbine

Christian Orgiazzi, Sylvain S. Guillou, Ottavio A. Lo Brutto, Alina Santa Cruz, Céline Mayousse, Mohamad N. Shiekh Elsouk, Alan Jean-Marie

Abstract— **Tidal turbines farms are used for harnessing kinetic energy from oceans. Prior to conceive a project with industrial interest, the analysis of hydrokinetic interactions between the devices in a tidal farm must be achieved. In fact, the power produced by a cluster of marine or tidal turbines is affected by the turbines' layout because of the wake effects. The latter can be analysed using analytical models because of their acceptable precision and lower computational cost compared to numerical models. In the literature, the existing analytical models for the analysis of the far wake of a standalone tidal turbine can be applied only in the case that the turbine wake expansion is symmetrical with respect to the axis of the device, in order to respect the hypothesis of self-similar wake or axial-symmetric wake. This is possible only in a limited set of conditions.**

The aim of this paper is to present a methodology to estimate analytically the tidal velocity in the far wake of a standalone tidal turbine installed on the seabed, considering the effect of the latter on the wake expansion. The model is developed using data from CFD simulations as a reference. In the numerical model, the turbine is represented by an actuator disc. The impact of the ambient turbulence will be considered in this study. This analysis will allow extending the applicability of the existing tidal turbine wake models..

Keywords— **Actuator Disc, Ambient Turbulence, Analytical Wake Model, Seabed-Mounted Turbine, Tidal Energy.**

I. Introduction

In the last decades researchers have focused their attention on Marine Renewable Energies in order to find solutions to mitigate the climate change through decarbonized systems. In particular, tidal energy attracted the interest of politics, scientists and industrials because it is highly predictable and because of the high energy potential of some sites. As an example, the French Government wants to invest to deliver large scale, cost competitive, predictable tidal power to the grid from the Alderney Race (Raz Blanchard in French). This site has more than 2GW of economically exploitable tidal resource [1]. The Normandy Region and the company SIMEC Atlantis Energy have formally announced in 2018 their intention to build Europe's largest tidal power array in the Alderney Race through a new Joint Venture Company called *Normandie Hydrolienne* [2].

One of the challenges of this type of project is the estimation of the Annual Energy Production (AEP), which is a fundamental performance parameter to determinate the financial viability. In order to calculate correctly the AEP of a tidal farm, it is important to predict the negative hydrodynamic interaction between the turbines. In fact, downstream devices extract less energy than upstream ones because of the wake effects. The wakes and, thus, the AEP depend on different parameters such as the number and characteristics of the devices (as the diameter and its geometry), the installation depth, the site hydrodynamic conditions (as the tidal speed and directional spreading and the ambient turbulence rate) and the turbines' longitudinal and lateral spacing. A theoretical study achieved in [3] showed that, in order to find a good compromise between reducing the wakes' interaction (easier with a low number of turbines), and having a sufficient overall production to lowering the installation costs, the longitudinal distance between two coaxial devices can be in the range of values between 10D and 45 D (where D is the diameter of the turbine). The optimal distance between two rows is highly impacted by the ambient turbulence rate of the exploited site. This parameter can vary between 6 and 25% in sites exploitable for tidal energy extraction [4-5]

The wake effect can be analysed both with numerical methods and with analytical methods [6]. It should be considered that one of the most important applications of wake models is the layout optimization. In this kind of application, the number of possible layouts increases with

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the number of devices. Moreover, the power produced by the farm has to be calculated considering all tidal directions, tidal speeds and their frequency of occurrence. If the objective is to find the optimal layout that minimizes the wake effect among all the possible combinations, the use of CFD-based models is not practically feasible [7]. For this motivation, in the last decade, some authors investigated the possibility of using simple analytical models, characterized by a low execution time and by an acceptable precision.

In the literature, it is possible to find two kinds of analytical tidal turbine wake models: the self-similarity based models and the axial-symmetry based ones. Stallard *et al.* [8] developed a semi-analytical wake model from measurements of a tidal turbine wake in shallow waters. Lo Brutto *et al.* [9-10] adapted the Jensen model from wind farm literature [11] in order to analyse the wake of a tidal turbine installed in deep waters. Both models are characterized by an high precision in their fields of application; however, they can be applied only in the case that the turbine wake expansion is symmetrical with respect to the axis of the device, in order to respect the hypothesis of self-similar wake (as in Stallard *et al.* [8]) or axial-symmetric wake (as in Lo Brutto *et al.* [9-10]). This could be possible only in a limited set of conditions, depending on the turbine depth and to the diameter to depth ratio. Most of the first generation tidal farms projects involve the use of seabed-mounted devices [12]. The effect of the seabed on the tidal turbine wake expansion cannot be taken into account with the existing analytical methodologies. In fact, the seabed effect is an intrinsic difficulty of all the kinematic models that assume axial-symmetry of self-similarity [13].

In the present paper the objective is to propose a methodology that permits to integrate the blockage effect of the seabed on the far wake expansion of a standalone tidal turbine. Thus, the effect of the mixing of several wakes is not considered in the paper. The applicability of the tidal turbine wake model presented in [10] (that considers a tidal turbine installed at mid-depth in deep waters) will be improved though the existing ground effect analysis in wind farm literature [13]. The ambient turbulence impact will be also considered in this analysis. The proposed model will be validated using a numerical model as a reference, in which the tidal turbine is represented by an Actuator Disc (AD) [14].

The wake model for one turbine is reanalysed in section II. The results of the proposed methodology for the estimation of the wake effect of one seabed-mounted tidal turbine wake prediction are presented in section III.

II. Theories and Basis

A. *Tidal turbine wake effect*

The wake is defined as a region behind a tidal turbine in which the turbulence rate increases and the flow velocity is reduced compared to the free flow characteristics.

The wake can be divided into two regions: the near wake and the far wake. In the first region (that vanishes at a distance of 5 D) there is a generation of turbulence because of the vortices shed by the blades and of the blades' motion. Moreover, an additional shear-generated turbulence is created by the fluid speed gradient between the wake and the free flow. This type of turbulence permits to transfer the momentum from the free stream to the wake, while the total momentum loss caused by the device is conserved. The mixing of the wake with the free flow makes the wake diameter expand, and the velocity deficit is recovered downstream. When the shear-generated turbulence has reached the centre of the wake, the far wake region starts. In this zone, the turbulence components generated by the turbine and its rotation are almost vanished, and the wake expansion is thus affected mainly by the ambient turbulence [15-17]. In order to analyse the hydrodynamic characteristics in the far wake, Jensen [11] developed a simple model in which the effect of the shear-generated and turbine-generated turbulences are neglected because of their minor role on the far wake expansion. According to the Jensen model, the tidal speed in the wake of a tidal turbine has a top-hat profile, and the wake expands with a linear growth, as shown in Fig.1 [18]. The velocity at any point in the far wake of a tidal turbine can be obtained through the momentum balance (1), in which U_w is the flow velocity at a downstream distance x, U_0 is the free stream velocity, U_{w0} is the minimum velocity in the wake calculated considering the Betz limit (2), r_0 is the radius of the turbine, C_T is the thrust coefficient, and r_w is the wake radius that is proportional to x, as shown by (3). The wake expansion r_w depends on the decay coefficient α.

$$\pi r_0^2 U_{w0} + \pi(r_w^2 - r_0^2)U_0 = \pi r_w^2 U_w \tag{1}$$

$$U_{w0} = U_0\sqrt{1 - C_T} \tag{2}$$

$$r_w = r_0 + \alpha x \tag{3}$$

Lo Brutto *et al.* [10] demonstrated that the wake decay coefficient of a tidal turbine can be expressed as a linear function of the ambient turbulence rate I_0:

$$\alpha = a_1 \cdot I_0 + a_2 \tag{4}$$

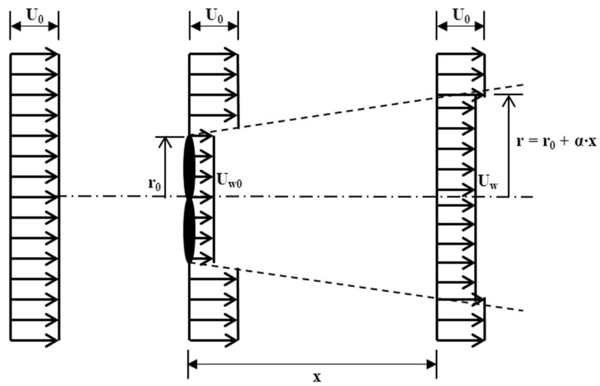

Fig. 1. Jensen model scheme for a turbine's wake.

where a_1 and a_2 are two coefficients that can be obtained by comparison with numerical or experimental data. The authors used the numerical model of [14] as a reference to obtain the following values for a tidal turbine installed at mid-depth in deep waters:

$$a_1 = 0.5\,;\, a_2 = 0.02 \tag{5}$$

The validity of these values for a seabed-mounted tidal turbine will be verified in section III.

B. *Considering the impact of the seabed on the wake expansion*

In the case the wake reaches the seabed, Eq. (1) cannot be applied for the calculation of the seabed. It is possible to find examples in wind turbine literature of possible solutions for the awareness of the seabed effect. One of the most used and efficient methods, that will be used in this work, is the one proposed by Frandsen [13]. According to the latter, it can be consider that, after the wake impacts the ground, the expansion of the wake is still axisymmetric, the total momentum deficit is conserved and the area of the wake can be computed by removing the circular segment below the seabed.

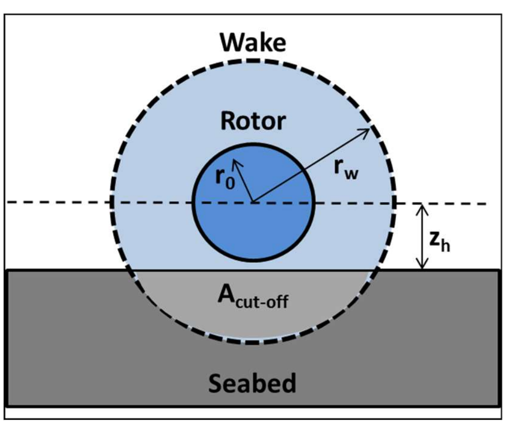

Fig. 2. Wake expansion in the transverse plan when the wake reaches the seabed.

Following this hypothesis, the Jensen model (1) can be modified as follow:

$$\pi r_0^2 U_{w0} + [\pi(r_w^2 - r_0^2) - A_{cut-off}]U_0 = (\pi r_w^2 - A_{cut-off})U_w \tag{6}$$

where $A_{cut\text{-}off}$ is the circular segment of the wake below the ground (see Fig. 2). This surface can be calculated as:

$$\begin{cases} A_{cut-off} = 0 & if\ r_w \le z_h \\ A_{cut-off} = r_w^2 cos^{-1}\left(\frac{z_h}{r_w}\right) - z_h\sqrt{r_w^2 - z_h^2} & else \end{cases} \tag{7}$$

where z_h is the tidal turbine hub depth and the wake radius r_w is still calculated with (3-4).

C. *Numerical Model presentation and method*

The numerical model proposed by Nguyen *et al.* [14] will be used in this work to obtain de reference data. The authors performed a three-dimensional numerical simulation of the flow in which the tidal device is represented with an Actuator Disc (AD). Thus, the rotor of the tidal devices is modelled with a disc in which the thrust is homogeneously distributed. The consequence of the application of this force is a change in momentum. It results a reduction of the kinetic energy on the flow and of the flow velocity downstream the rotor. The thrust force depends on the differential pressure between both sides of the disc ΔP, on the disc area A_T, on the free-flow velocity U_0, on the fluid density ρ, and on the thrust coefficient C_T, as show in (8). The thrust created by the disc on the flow is introduced in the steady-state Navier-Stokes Equations (NSEs) as a sourced term S_i, calculated with (9), in which K is the resistance coefficient, e the thickness of the disc and U_d the velocity at the disc location. The relation between the thrust coefficient C_T and the resistance K is shown by (10).

$$F_T = A_T \Delta P = \frac{1}{2} C_T \rho A_T U_0^2 \tag{8}$$

$$S_i = -\frac{F_T}{A_T e} = -\frac{1}{2}\rho\frac{K}{e}U_d^2 \tag{9}$$

$$C_T = \frac{K}{(1 + 0.25K)^2} \tag{10}$$

The equations introduced before are solved using FLUENT ANSYS 14.5, using the k-ε turbulence model.

The numerical model was validated through the comparison with the experimental data presented in [19] (the validation of the model is presented in detail in [14]). In that case the resistance coefficient K is equal to 2 which corresponds to the thrust coefficient C_T = 0.86 available in the experiment of [19]. The sensitivity analysis was done in [14]. The mesh is covered with about 16 million of elements with a refinement in the vicinity of the disc (*Δx=Δy=Δz=D/100*) and of its wake. Velocity and turbulence profiles fitting the inlet experimental data were used as inlet boundary conditions. For *x=4D*, the error is 14% for the turbulence intensity and 19% for the axial velocity, then the maximum percentage error in the estimation of the velocity and the turbulence intensity in the far wake (*x/D>5D*) was less than 8%, as shown in Fig. 3 [14].

III. EMPIRICAL FAR WAKE MODEL PROPOSITION

D. *Numerical configuration and wake characteristics data*

CFD model of [14] was used to obtain full scale data for the improvement of the analytical model presented in [10]. One tidal turbine placed in a race like the one in Alderney (Raz Blanchard in French) has been analysed. Thus, a depth H of 50 m was considered, with a mean spring velocity of 3 m/s [20]. Concerning the ambient turbulence rate I_0 of this race, nowadays there are no available measured data. Thus, in our study different ambient turbulence rates from 5% to 15 % will be tested. These values were chosen in agreement with available measurements at comparable tidal sites [4-5].

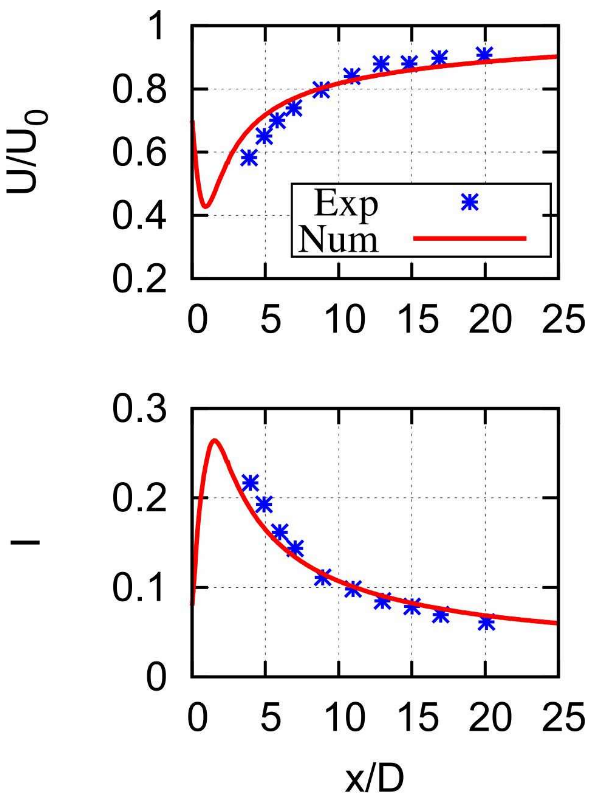

Fig. 3. Comparison between Harrison's experimental data and numerical results of the normalized axial velocity and turbulence intensity along the turbine axis [14].

A turbine with a 10m-diameter (D) rotor installed at 10 meters from the seabed was considered. That means that the distance between the tip of the blade and the ground is 5 m. This value is consistent with the state of the art of seabed-mounted devices [21].

In that concerning the computational domain, we considered a length of 600m and a width L of 400m, as shown in Fig. 4. The tidal turbine is located 20D from the inlet. A hexahedral mesh of 13,000,760 elements with a refinement in the area of the disc was used in this work. An inflation of the mesh is realized near the bottom with a growing factor of 1.2.

No-slip condition was imposed on the seabed, while a slip condition was used at the free surface, and symmetry conditions were considered on the lateral faces. A static pressure is fixed at the outlet. The inlet velocity $U_I(z)$, the intensity profile of the turbulent kinetic energy $k(z)$, and the dissipation of k are calculated using (11):

$$U_I(z) = 2.5U^* ln\left(\frac{z}{z_0}\right);\ k = \frac{3}{2}I^2U^2;\ \varepsilon = C_\mu^{3/4}\frac{k^{3/2}}{l} \quad (11)$$

where U^* is the friction velocity, equal to 0.1109 m/s, z is the distance from the bottom, z_0 is the roughness height, equal to 0.001 m, U is the mean inlet velocity, equal to 2.7 m/s, I is the turbulence intensity, $l=0.07H$ is the characteristic length [14]. Those values allow obtaining the velocity profile shown in Fig. 5.

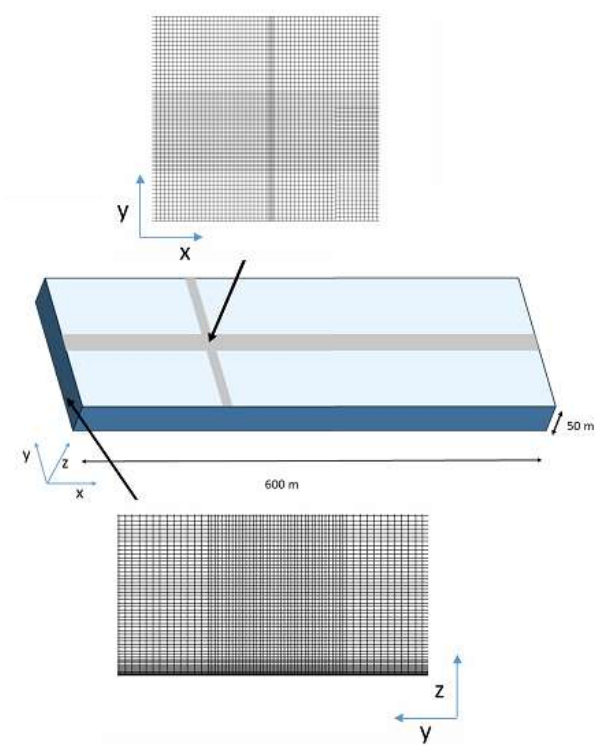

Fig. 4. Computational domain with the localization of the turbine and the mesh.

This correspond to the exponent coefficient n=1/8 proposed in [22]. Simulations have been provided for three turbulence intensities at the turbine (5%, 10% and 15% before the turbine). In order to do that and because the turbulence is decreasing along the channel (Fig. 5 bottom), the turbulence intensity I_H is fixed to respectively 6, 13 and 20% at the inlet (Fig. 5 middle).

CFD simulations allowed obtaining the flow velocity $U_{W,CFD}$ corresponding to the maximum deficit in the wake of the tidal turbine, for different values of downstream distance x and of ambient turbulence rate I_0. The results of the simulations are shown in Fig. 6. CFD data permitted analyzing also the impact of the seabed on the wake expansion. In fact, it can be noticed from Fig. 7 (in which the flow speeds are normalized on the hub-height freestream flow speed) that the degrees of freedom of the wake radius are limited by the presence of the ground, once the wake radius exceeds the tidal turbine hub-depth z_h.

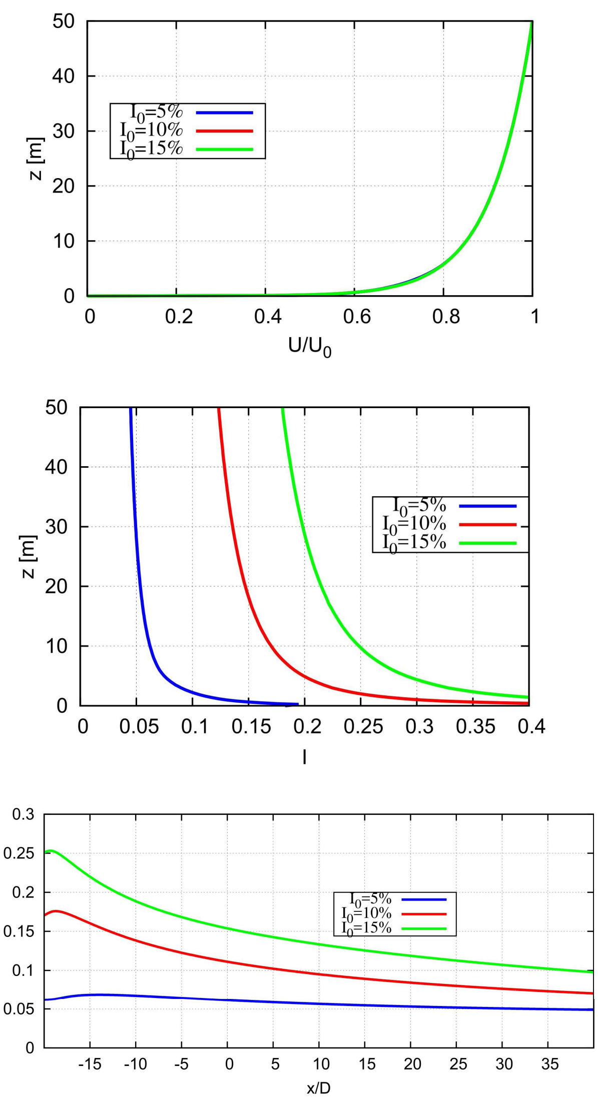

Fig. 5. Normalized Inlet velocity $U_I(z)$ profile (top), inlet turbulence intensity profile (middle) and evolution of the turbulence intensity on the turbine's axis (simulation without the turbine).

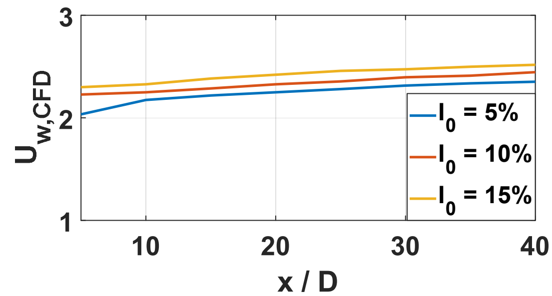

Fig. 6. Flow velocity profiles for different values of downstream distance x and of ambient turbulence rate I_0 obtained with CFD model.

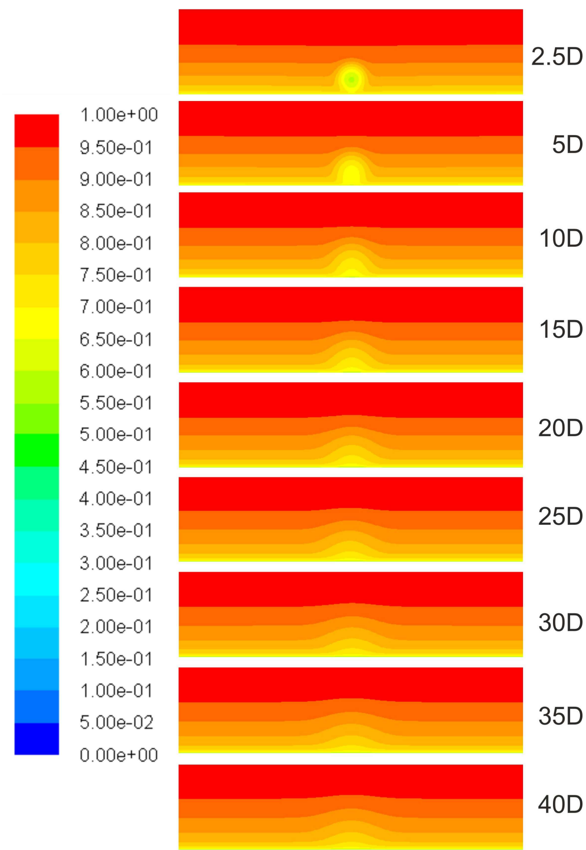

Fig. 7. Example of wake expansion in the transverse plane (y-z) obtained with CFD simulations at different downstream distances and I_0 = 5%. The flow speeds are normalized on the hub-height freestream flow speed.

E. Estimation of the average incoming fluid speed on the turbine

In tidal turbine analytical wake analysis, when the tidal turbine is placed at mid-depth, the approximation of considering the average incoming fluid speed U_0 equal to the mean inlet velocity U was adopted [8-10].

When analysing a seabed-mounted tidal turbine, this approximation could bring to a significant error because the device experiences the high gradient region of the inlet velocity profile (see Fig. 5). In order to obtain the average value of the speed at the inlet of the turbine, the following equation should be solved (see Fig. 8):

$$U_{o,av} = \frac{2\int_{z_h-r_0}^{z_h+r_0} U_I(z)\,dc dz}{\pi r_0^2} = \frac{2\int_{z_h-r_0}^{z_h+r_0} U_I(z)\,r_0\cos\theta dz}{\pi r_0^2} \quad (12)$$

where $dc=r_0 cos\theta$. Considering (11) and:

$$z - z_h = r_0 sin\theta \;;\; cos\theta = \sqrt{1 - sin_\theta^2} \quad (13)$$

equation (12) can be rewritten as:

$$U_{o,av} = \frac{2\int_{z_h-r_0}^{z_h+r_0} 2.5U^* ln\left(\frac{z}{z_0}\right) r_0 \sqrt{1-\left(\frac{z-z_h}{r_0}\right)^2}\,dz}{\pi r_0^2} \quad (14)$$

The integral in (14) was solved using the *integral* function on Matlab®. The values of the parameter indicated in Section III-A allow obtaining a mean value $U_{0,av}$ of 2.544 m/s.

F. *Estimation of the wake velocity at the turbine axis*

The objective now is to obtain the values of the coefficients a_1 and a_2 in (4). To this scope, the *nlinfit* function of Matlab® has been used [23]. This function allows obtaining the coefficients through the nonlinear regression method. This function requires an X matrix of predictor variables, a vector Y (having the same number of lines as X) of response values (dependent variable) for fitting the nonlinear regression function, a vector "*beta0*" of initial values of the coefficients to be determined, a nonlinear regression model, which must accept two input arguments (the coefficient vector "*beta0*" and the matrix X) and return a vector of estimated response values. In our case:

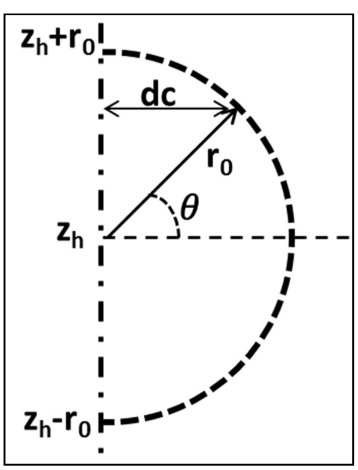

Fig. 8. Half of the surface of the tidal turbine for averaged input speed calculation.

- X is a two-column matrix in which the first column represents the values of the downstream distance of the turbine normalized with respect to the diameter of the turbine x/D, and the second column represents the ambient turbulence values;
- The value of the element n of the vector Y corresponds to the value of the wake velocity $U_{w,CFD}$ when the downstream distance x/D and the ambient turbulence I_0 are equal to the values *(n; 1)* and *(n; 2)* in the matrix X, respectively ;
- The vector "*beta0*" contains two initial values for a_1 and a_2 equal to the ones indicated in (5);
- The nonlinear regression model is obtained by implementing (2-4, 6, 7).

The use of the *nlinfit* function made it possible to obtain the following values for the coefficients of Eq. (4):

$$a_{1,sm} = 0.6908\,;\; a_{2,sm} = 0.0205 \quad (15)$$

where the index *sm* indicates that these values where obtained for the seabed-mounted turbine. The first interesting result we can notice is that the parameters in (15) are different to the ones of (5). That indicates that the seabed has a non-negligible impact on the wake characteristics.

The comparison in terms of minimum wake velocity between the reference data and the results of the proposed empirical model is presented in Fig 9, while Fig. 10 shows the errors of the proposed model in terms of estimation of the speed in the wake, calculated as:

$$\varepsilon(I_0) = \frac{U_w(I_0) - U_{w,CFD}(I_0)}{U_{w,CFD}(I_0)} \quad (16)$$

The average values of the errors according to the value of the ambient turbulence are summarized in Table 1.

It can be noticed that the proposed model allows estimating the wake characteristics with an average percentage error lower than 6% in all the cases (see Table I). The errors are close to or higher than 10% only at axial distance x equal to 5D. This discrepancy can be explained considering the limitation of the Jensen model discussed in Section II.A, that is that the effect of the shear-generated and turbine-generated turbulences are neglected. In the literature, the axial distance x = 5D is indicated as the limit between the near wake and the far wake [13,15]. The results suggest that the neglected turbulences impacts the precision of the results in the limit between the near wake and the far wake. However, as discussed in section I, a longitudinal distance of 5D is out of the range of interest of future commercial tidal farms configuration, that is between 10D and 45D (depending on the ambient turbulence rate of the exploited site), in order to have a good compromise between an high amount of produced power and acceptable Capital Expenditure (Capex) and Operational Expenditure (Opex), factors affecting the Cost of Energy [24-25].

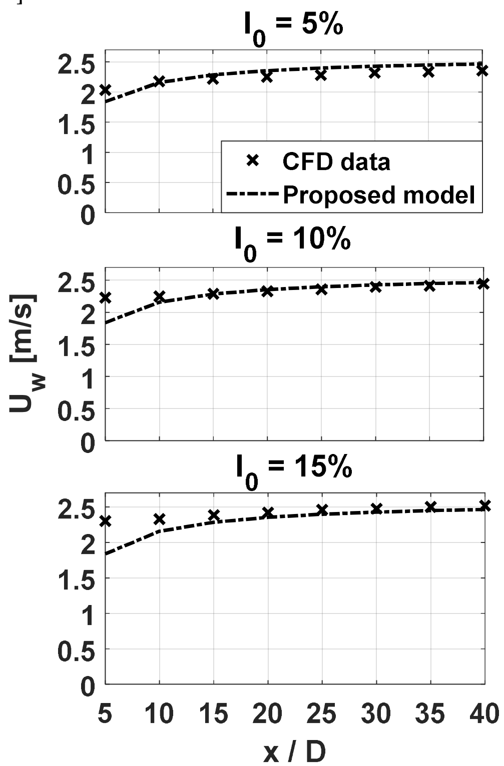

Fig. 9. Comparison in terms of minimum wake velocity between the reference CFD data and the results of the proposed model.

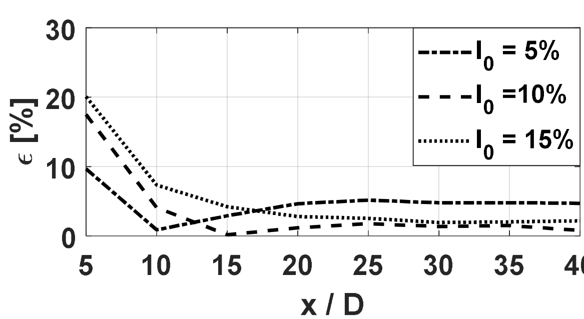

Fig. 10. Error in estimating the minimum wake velocity with the proposed model using (14).

TABLE I
ERRORS OF THE PROPOSED MODEL IN TERMS OF ESTIMATION OF THE SPEED IN THE WAKE

	$I_0 = 5\%$	$I_0 = 10\%$	$I_0 = 15\%$
Average estimation error	4.6869	3.5372	5.3810

IV. Discussion and Conclusions

This work has introduced a methodology to take into account the effect of the seabed on the far wake characteristics of a standalone tidal turbine. This analysis has been realized through the Jensen's momentum balance on the device, coupled with the calculation of the circular segment of the wake below the ground. The effect of the shear-generated and turbine-generated turbulences were neglected because of their minor role on the far wake expansion, thus only the impact of the ambient turbulence rate was considered in the paper. The parameters of the model were obtained through a non-linear regression method. Results indicate that the model is able to estimate the flow velocity in the wake of a tidal turbine with an average error lower than 6%. In order to demonstrate the predictive ability of the modified Jensen model and to analyse some of the key physics in tidal wake phenomenon, more test case will be conducted in future works.

Another point to be investigated concerns the importance of the inlet profile analysis. Some articles indicate that the velocity profile in tidal sites could be homogeneous with a power law in 1/7 or 1/6 [26-28]. This induces real differences close to the bottom and a greater impact on the turbines' wake as the one used in this paper. This must deserve a particular study to improve the presented model.

The analysis of the wake of one tidal turbine is a starting point for the study of a tidal farm, where the interaction of multiple wakes occurs. The effect of the neighbouring turbines of the far wake on a turbine in a park will be the object of further development.

The most important result of the present paper is that the model's parameters obtained to estimate the wake expansion of a seabed-mounted tidal turbine are different to the one obtained for a mid-depth mounted tidal turbine. This indicates that the seabed impacts the flow characteristics in the wake of the turbine. Realistically, it can be supposed that the turbine installation depth should be in general taken into account for the producible energy estimation of a tidal farm. That implies that the impact of the sea free surface should be equally considered in the tidal turbine wake hydrodynamic analysis. This study is the subject of ongoing research works.

References

[1] L. E. Myers and A. S. Bahaj, "Simulated electrical power potential harnessed by marine current turbine arrays in Alderney Race," *Renew. Energy*, vol. 30, pp. 1713–1731, 2005.

[2] L'Usine Nouvelle, "La Normandie investit dans un projet hydrolien au Raz Blanchard," Oct. 2018. [Online] Available: https://www.usinenouvelle.com/article/la-normandie-investit-dans-un-projet-hydrolienne-du-raz-blanchard.N762719

[3] O.A. Lo Brutto, J. Thiébot, S.S. Guillou, and H. Gualous, "A semi-analytic method to optimize tidal farm layouts–

Application to the Alderney Race (Raz Blanchard), France," *Applied Energy*, vol. 183, pp. 1168-1180, 2016.

[4] I.A. Milne, R.N. Sharma, R.G.J. Flay, and S. Bickerton, "Characteristics of the turbulence in the flow at a tidal stream power site," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 371, issue 1985, p. 20120196, 2013.

[5] J. Thomson, B. Polagye, V. Durgesh, and M.C. Richmond, "Measurements of turbulence at two tidal energy sites in Puget Sound, WA," *IEEE Journal of Oceanic Engineering*, 2012; vol. 37, issue 3, pp. 363-374, 2012.

[6] M. Palm, R. Huijsmans, and M. Pourquie, "The applicability of semi-empirical wake models for tidal farms," in *Proceedings of the 9th European Wave and Tidal Energy Conference 2011*.

[7] C. L. Archer, A. Vasel-Be-Hagh, C. Yan, S. Wu, Y. Pan,J.F. Brodie, and A. E. Maguire, " Review and evaluation of wake loss models for wind energy applications," *Applied Energy*, vol. 226, pp. 1187-1207, 2018

[8] T. Stallard, T. Feng, and P.K. Stansby, "Experimental study of the mean wake of a tidal stream rotor in a shallow turbulent flow," *J. Fluids Struct*., vol. 54, pp. 235–46, 2015

[9] O.A. Lo Brutto, V.T. Nguyen, S.S Guillou, J. Thiébot, and H. Gualous H, "Tidal farm analysis using an analytical model for the flow velocity prediction in the wake of a tidal turbine with small diameter to depth ratio," *Renew Energy,* vol. 99; pp. 347–59.

[10] O.A. Lo Brutto, V.T. Nguyen, S.S. Guillou, H. Gualous, and B. Boudart, "Reanalyse of an analytical model for one tidal turbine wake prediction," in *Proceedings of the 11th European Wave and Tidal Energy Conference*, 2015 (Nantes, France).

[11] N. Jensen, "A Note on Wind Turbine Interaction," Technical Report Ris-M-2411, Risø National Laboratory, Roskilde, Denmark, 1983.

[12] S. Bala, J. Pan, G. Barlow, G. Brown, and S. Ebner, "Power conversion systems for tidal power arrays," in *IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2014.

[13] A. Crespo, J. Hernandez, and S. Frandsen, "Survey of modelling methods for wind turbine wakes and wind farms," *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*, vol. 2, issue 1, pp; 1-24, 1999.

[14] V.T. Nguyen, S.S. Guillou, J. Thiebot, and A. Santa Cruz, "Modelling turbulence with an actuator disk representing a tidal turbine," *Renew. Energy,* vol. 97, pp. 625-635, 2016.

[15] P.E.J. Vermeulen, "An experimental analysis of wind turbine wakes," in *3rd international symposium on wind energy systems*, 1980. pp. 431-450.

[16] F. Maganga, G. Germain, J. King, and E. Rivoalen, "Experimental characterisation of flow effects on marine current turbine behaviour and on its wake properties", *IET Renewable Power Generation*, vol. 4, no 6, pp. 498-509, 2010.

[17] P. Mycek, B. Gaurier, G. Germain, G. Pinon, and E. Rivoalen, "Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: One single turbine", *Renewable Energy*, vol. 66, pp. 729-746, 2014.

[18] C.H. Jo, J.H. Lee, Y.H. Rho, and K.H. Lee, "Performance analysis of a HAT tidal current turbine and wake flow characteristics," *Renewable Energy*, vol. 65, pp. 175-182, 2014.

[19] M.E. Harrison, W.M.J. Batten, L.E. Myers, and A.S. Bahaj, "Comparison between CFD simulations and experiments for predicting the far wake of horizontal axis tidal turbines," *IET Renewable Power Generation*, vol. 4, no 6, pp. 613-627, 2010.

[20] J. Thiébot, P. Bailly du Bois, and S.S. Guillou, "Numerical modeling of the effect of tidal stream turbines on the hydrodynamics and the sediment transport–Application to the Alderney Race (Raz Blanchard), France," *Renewable Energy,* vol. 75, pp. 356-365, 2015.

[21] Z. Zhou, M. Benbouzid, J.F. Charpentier, F. Scuiller, and T. Tang, "Developments in large marine current turbine technologies–A review," *Renewable and Sustainable Energy Reviews*, vol. 71, pp. 852-858, 2017.

[22] T. Daly, L.E. Myers and A.S. Bahaj., Modelling of the flow field surrounding tidal turbine arrays for varying positions in a channel, Philosophical transactions of the royal society A, 371, 20120246, 2012.

[23] Matlab, "Nonlinear regression," 2018. [Online] Available: https://fr.mathworks.com/help/stats/nlinfit.html

[24] S. W. Funke, S. C. Kramer, M. D. Piggott, "Design optimisation and resource assessment for tidal-stream renewable energy farms using a new continuous turbine approach," *Renewable energy*, vol. 99; pp.1046-1061, 2016.

[25] A. Vazquez, G. Iglesias, "Grid parity in tidal stream energy projects: An assessment of financial, technological and economic LCOE input parameters", *Technological Forecasting and Social Change*, vol. 104; pp. 89-101, 2016.

[26] G. McCann, M. Thompson, S. Hitchcock, "Implications of Site-Specific Conditions on the Prediction of Loading and Power Performance of a Tidal Stream Device", in *2nd International Conference on Ocean Energy (ICOE 2008)*, 15th – 17th October 2008, Brest, France.

[27] D.R.J. Sutherland, D. R. Noble, J. Steynor, T. Davey, T. Bruce, "Characterisation of current and turbulence in the FloWave Ocean Energy Research Facility", *Ocean Engineering*, vol. 139; pp. 103–115, 2017.

[28] A. Mason-Jones, D.M. O'Doherty, C.E. Morris, T. O'Doherty, "Influence of a velocity profile & support structure on tidal stream turbine performance", *Renewable Energy*, vol. 52; pp. 23-30, 2013.