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J. Tondut, T. El Tawil, J. Thiébot, Nicolas Guillou, M. Benaouicha. A comparative study for tidal current velocity prediction using simplified and fast algorithms. *Applied Ocean Research*, 2020, 104, pp.102346. 10.1016/j.apor.2020.102346 . hal-03054549

HAL Id: hal-03054549

<https://hal.science/hal-03054549>

Submitted on 5 Sep 2022

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A comparative study for tidal current velocity prediction using simplified and fast algorithms[★]

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ARTICLE INFO

Keywords:

Tidal Stream Energy, Tidal Current Prediction, Advanced Linear Approximation, Computational Method, Site Evaluation, Fromveur Strait, Alderney Race.

ABSTRACT

Interest in marine renewable energies has grown in recent years, especially in northern European shelf seas where several technological devices have been developed. In this context, numerous investigations focused on accurate predictions of tidal currents and their respective kinetic energy. An empirical estimation of the current velocity is explored in this study, where three different methods are presented. The first method is a linear approximation of the tidal vector velocity as a function of the tidal coefficient. The second method is a piece wise linear model and finally an exponential relation between tidal vector velocity and the tidal coefficient lead to results improvements. These three methods are compared to reference values obtained using a numerical simulation of tidal circulation. These methods are applied at two prominent tidal stream energy sites along the coast of France, the Fromveur Strait (western Brittany) and the Alderney Race (west English Channel). Results show that the linear advanced and the exponential models are more accurate than the linear approximation.

1. Introduction

During the last decade, a growing interest has been brought to the development of technologies liable to produce renewable energies and reduce carbon dioxide emissions. Therefore, wind turbines and solar panels are increasingly present in modern grids. Another sustainable power production that has recently emerged, is based on the exploitation of renewable marine energy focusing especially on the tidal stream energy resource. The European potential associated with the kinetic energy of tidal currents is estimated at a 12,500 MW installed capacity [2]. However, technologies for tidal kinetic energy conversion are still not mature and require technological improvements before being economically viable. One of the major technological limitations is the adjustment in real time of the turbine settings as a function of the incoming current velocity magnitude for optimising power production. Accurate assessments of the direction and magnitude of the tidal current are required at any time to set and to anticipate the machine adjustments [1, 6, 5]. A simple manner to compute tidal velocity is thus required to control the orientation and rotational speed of the turbine's blades, and therefore adapt nominal power production [7].

To assess the resource of potential tidal stream energy sites (tidal current magnitude and direction), Acoustic Doppler Current Profiler (ADCP) measurements are typically implemented [8, 3]. However, these observations are limited to a number of time periods and locations. Projects on marine power production require thus a significant amount of data (covering seasonal or annual time scales) to determine tech-

nological options and optimal locations of energy converters in the marine environment. The use of such ADCP data is not sufficient by itself. Therefore, other methods such as numerical simulations or tidal harmonic analysis have been developed to predict current speed and directions [10, 11, 15, 4]. While being a well tried method to estimate tidal currents in the marine environment, tidal numerical modelling, requires high computational capacities. In order to reduce the computational time, El Tawil et al. [7] have proposed an empirical method to approximate tidal current velocities as a function of the (i) tidal range and (ii) reference values $\overline{V}_{45}(t_i)$ and $\overline{V}_{95}(t_i)$, that accounts for the velocity vectors in mean neap and spring tidal cycles, respectively. Those reference values can be easily provided by numerical simulations (Section 2) or on-site observations.

This paper extends the analysis of El Tawil et al. [7] on the relationship between current velocity and tidal range. El Tawil et al. [7] assumed a linear relation. The present investigation conducts an improvement of this linear approximation by using a piece-wise linear model and an exponential method. The results from the above methods are calibrated and validated against reference values obtained using numerical simulations of the tidal circulation [13]. To assess the performance of the advanced linear and the exponential models, the computed velocities are compared to these reference values at two sites with strong potential for the exploitation of the tidal stream energy resource along the coast of France: the Fromveur Strait in western Brittany and the Alderney Race in the English Channel (Fig. 1). The overall objective of this study is to assess the reliability of a simple empirical model or an exponential relationship to represent the whole, or a part of the tidal flow complexity. Furthermore, the advanced linear and exponential methods require few input data and provide fairly good approximations of the

[★]Numerical simulations in the Brittany region were conducted on HPC facilities DATARMOR of "Pôle de Calcul et de Données pour la Mer" (PCDM) (<http://www.ifremer.fr/pcdm>).

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tidal currents while sparing computational time.

The paper is organized as follows: Section 2 describes successively the linear approximation method (i), the advanced linear method (ii), and the exponential method developed (iii) to enhance tidal current velocity predictions. Section 3 shows results, compares and discusses these three methods presented. Conclusions are finally drawn in Section 4.

2. Methods

2.1. Study sites

The tidal hydrodynamic conditions of the Fromveur Strait and the Alderney Race are briefly described by relying on numerical predictions. The reference data for the empirical model calibration and validation are provided by Telemac3D, a three-dimensional finite element model which solves the continuity and averaged momentum equations [13]. The hydrodynamic data are derived from the numerical model set up by Guillou and Chapalain [9]. The computational grid was composed of 51,226 nodes duplicated along the vertical direction with 15 terrain following sigma-levels [12] in Western Brittany. This grid has a high spatial resolution smaller than 50 m in the area of interest where the current is the strongest and larger than 10 km at offshore sea boundaries. The numerical simulation is conducted during the year 2016. The model is validated against a series of ADCP measurements. The simulation performed within the Alderney Race relies on the bi-dimensional model Telemac2D that solves the shallow-water Barré de Saint-Venant equations of continuity and momentum. The computation is conducted on a domain composed of 14,192 nodes with cell sizes varying from 150 m in the Alderney Race to 10 km at offshore sea boundaries [15]. The simulation is performed during the year 2005 and validated against a series of ADCP measurements [15].

In the present investigation, two sites located along the coast of France are considered. The first one is located in western Brittany, within the Fromveur Strait. This strait separates the island of Ouessant from the Molène archipelago through a 2 km wide and 50 m deep strait (Fig. 1.a). Three locations are selected in the area with the highest kinetic energy tidal potential (Fig. 1.a and Tab. 1). The hydrodynamic of the Fromveur Strait is characterised by a strong asymmetry in tidal currents magnitude. The north-east part of the strait is thus dominated by flood flow whereas the south area is dominated by ebb current [9, 11]. This asymmetry in current magnitude is exhibited in Fig. 2, with differences between predictions of the peak-flood and the peak-ebb magnitudes. In Figure 2, the tidal period considered starts with a rising tide. The maximal speed is thus reached during the flood tide at P1 whereas it is reached during ebb tide at P3.

The second site, located within the English Channel, is the Alderney Race (Fig. 1.b) between the Alderney Island and La Hague Cape [15]. This high potential site for a tidal stream farm presents currents peaks reaching 5 m/s during spring tides. These strong currents are mainly due to the acceleration of the tidal flow between Alderney Island and

Table 1

Characteristics of locations P1, P2 and P3 in the Fromveur Strait (Fig. 1.a)

Locations	Longitude	Latitude	Mean water depths
P1	5.049° W	48.438° N	58 m
P2	5.034° W	48.447° N	56 m
P3	5.019° W	48.454° N	54 m

Table 2

Characteristics of locations P1 and P2 in the Alderney Race (Fig. 1.b).

Locations	Longitude	Latitude	Mean water depths
P1	-1.964° W	49.745° N	50 m
P2	-2.019° W	49.720° N	50 m

the Cape of La Hague [15]. Two locations with contrasted current characteristics but similar water depth (50 m) are selected (Tab.2). The asymmetric behavior in the English Channel is less important than in the Fromveur Strait. Figure 3 shows the differences in velocity peak for both flood and ebb flows cases in the Alderney Race. This reduced tidal current asymmetry is consistent with the results obtained by Guillou et al. [11] by exploiting a high-resolution harmonic tidal current database in the western English Channel.

2.2. Linear Method

The linear method presents a relation between the tidal current velocity vector and the tidal range, in order to derive an empirical relation between both quantities [7]. To this end, first the notion of tidal coefficient (c) is introduced and defined as the ratio between (i) the tidal range resulting from semi-diurnal harmonic components and (ii) a reference value taken at the harbour of Brest (western Brittany) as equal to 6.1 m. This ratio is commonly multiplied by 100. This coefficient that accounts for the rise of the tide along the coast of France varies between 20 for exceptional neap tidal conditions (lowest tidal range) and 120 for exceptional spring conditions (highest tidal range). Tidal coefficients of 45 and 95 correspond to mean-neap and mean-spring tidal conditions, respectively. Further details about the approximation of the vector velocity \vec{V} as a function of the tidal coefficient are available in [7].

For the Fromveur Strait, a neap ($c = 45$) tidal period was identified, for the year 2016, from March 17th at 18h36 to March 18th at 00h53 (UTC+2). Corresponding time-series of current magnitude are plotted in Figure 2.a. Concerning spring ($c = 95$) tidal cycle, a period which started at 12h03 (UTC+2) on 11 January and ended at 18h01(UTC+2) is shown in Figure 2.b. The tidal coefficients and hours of high and low tides are provided by the French Navy SHOM (Service Hydrographique et Océanographique de la Marine) database for the year 2016 in the harbour of Brest [14].

For the Alderney Race, the neap tidal cycle $\overline{V}_{45}(t_i)$ occurred on 3 February from 7h48 to 20h23 (UTC+2). The spring tidal cycle $\overline{V}_{95}(t_i)$ started at 14h06 on the 8th of February to February 9th to 2h29 (UTC+2). The comparison of

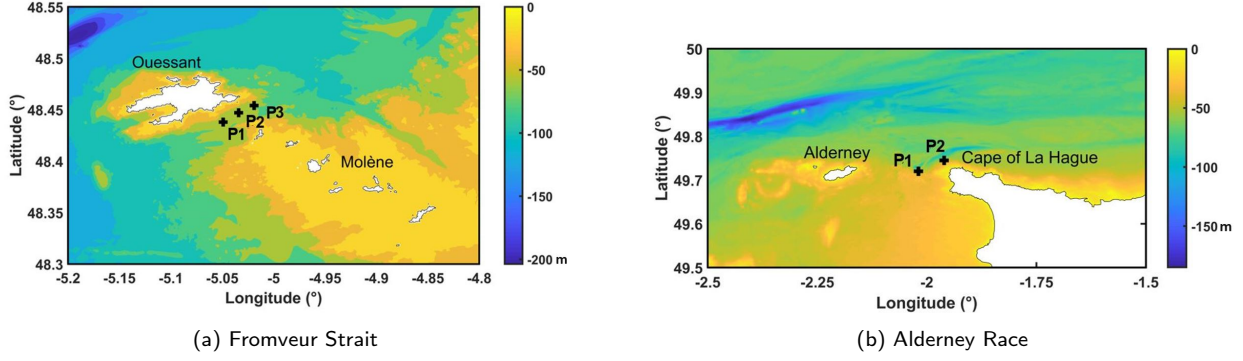


Figure 1: Bathymetry of the area surrounding (a) the Fromveur Strait and (b) the Alderney Race with locations considered for the analysis of tidal current predictions.

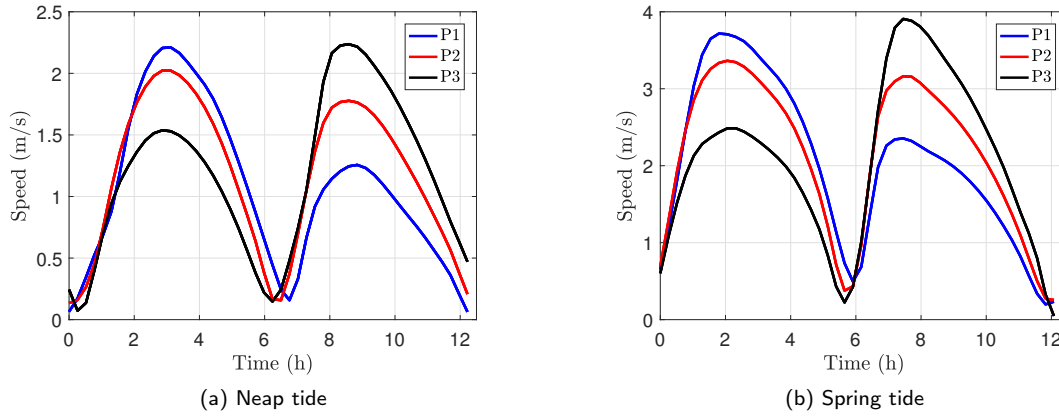


Figure 2: Reference time series of velocity magnitude V_{45} at neap and V_{95} at spring tidal conditions for the three points considered in the Fromveur Strait.

Figure 3.a and 3.b indicates that the magnitude differs between neap and spring conditions. The tidal coefficients exported from the SHOM for the year 2005 and tidal periods are taken in the nearest harbour, Goury.

2.3. Advanced Linear Method

The results of the linear method presented in [7] are firstly compared to the reference data obtained using the numerical models. The error of the linear method is assessed with the relative difference between peak velocities for a given tidal coefficient and is further discussed in [7].

The variation of the mean relative error between the numerical and the linear methods are shown in Figure 4 for the point P2. At the Fromveur Strait, the error is mainly lower than 8%, however, under extreme conditions ($c < 35$ or $c > 105$) the error increases and varies between 8 and 16%. At the Alderney Race, the error is mainly under 20% and varies from 20 to 80% during exceptional tides ($c < 35$ or $c > 105$).

The error reaches its minimum at $c = 45$ and $c = 95$ since these are references values. The tidal velocity is furthermore underestimated for low tidal coefficients and high tidal coefficients. The fit of the empirical law is less good

for extreme coefficients. All five points in both locations show similar trend curve. The error can however be approximated by two linear curves. The first one on the interval $c = [20; 70]$ and the second one for $c = [70; 120]$, as shown in Figure 4 with the dashed black line for both locations. To simplify the graphs, Figure 4 only considers the point P2. The error analysis leads to correct the linear method (Section 2.2) using the following relation:

$$\overline{V}(t_i) = \begin{cases} \overline{V}_{45}(t_i) + \frac{c-45}{95-45}(\overline{V}_{95}(t_i) - \overline{V}_{45}(t_i)) - \left(\frac{v_{70}-v_{45}}{70-45} \times c - \frac{v_{70}-v_{45}}{70-45} \times 70 + v_{70}\right) & \text{if } c < 70 \\ \overline{V}_{45}(t_i) + \frac{c-45}{95-45}(\overline{V}_{95}(t_i) - \overline{V}_{45}(t_i)) - \left(\frac{v_{95}-v_{70}}{95-70} \times c - \frac{v_{95}-v_{70}}{95-70} \times 70 + v_{70}\right) & \text{if } c \geq 70 \end{cases} \quad (1)$$

This piece-wise linear function seems to be adapted for the different locations of periods to time considered.

2.4. Exponential Method

A further investigation of the relation between the tidal coefficient and the peak velocity, is shown in Figure 5, where

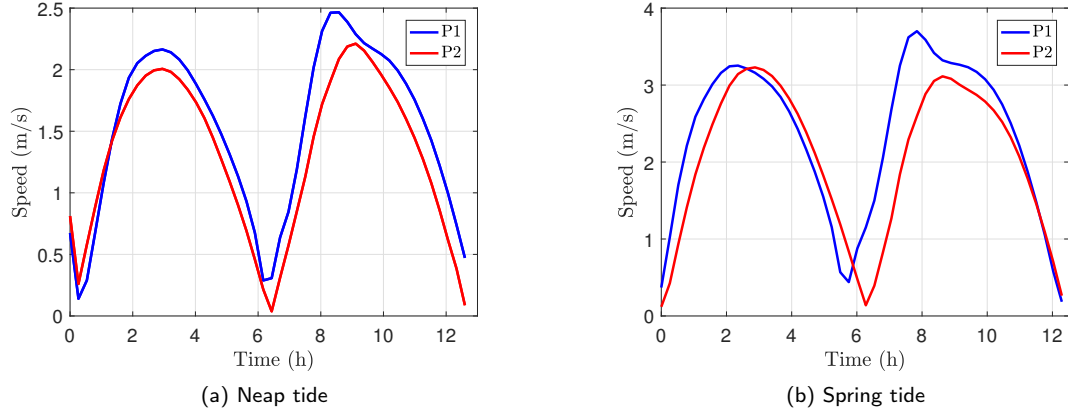


Figure 3: Reference time series of velocity magnitude V_{45} at neap and V_{95} at spring tidal conditions for the two points considered in the Alderney Race.

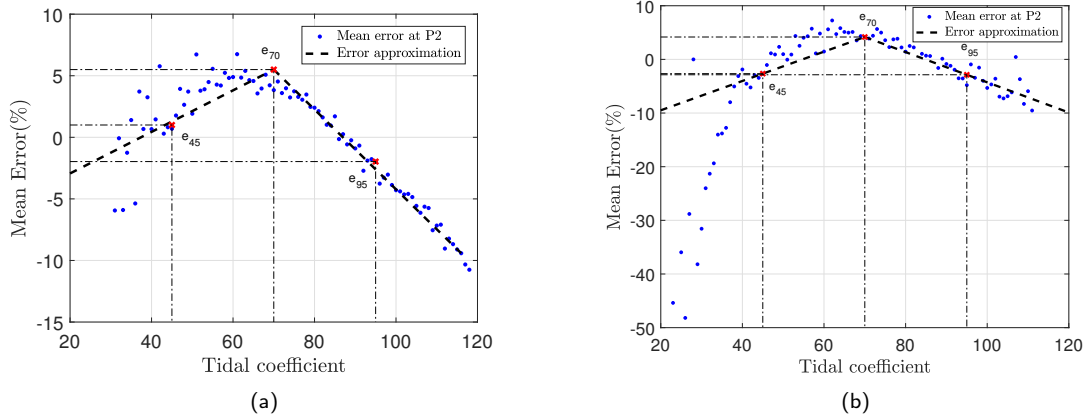


Figure 4: Variation of the relative difference e_c according to the tidal coefficient c for the year 2016 in the Fromveur Strait at P2 (a) and for the year 2005 in the Alderney Race at P2 (b).

the clouds of dots come from numerical computation for the Fromveur Strait (a) and the Alderney Race (b), respectively. An exponential relation seems to fit the curve with accurate precision. Equation 2 presents this exponential equation.

$$v_{max}(c) = \alpha \times \left(1 - e^{-\left(\frac{c}{\beta}\right)}\right) \quad (2)$$

Figure 5 illustrates the exponential approximation and the reference values similar and close variation. The values of α and β are calculated by solving a two equations with two variables, obtained by using the reference velocities at $c = 45$ and $c = 95$. Their values are summarized in the Table 3 for both sites.

Finding these two values α and β , requires no more than two reference values provided by measurements or numerical computation. The Equation 2 can be applied after the advanced linear method to estimate correcter coefficient that improves the accuracy of the computation. Thus, the current

velocity V_{cor} is thus corrected as the following relation:

$$V_{cor} = V_{lin} \times \frac{\alpha(1 - e^{-\left(\frac{c}{\beta}\right)})}{\max(V_{lin})} \quad (3)$$

where V_{lin} is the current velocity computed with the basic linear function (Section 2.2).

3. Results and Discussion

The relative errors between reference values current velocity and the current velocities performed by the different methods are computed. Results of the three different methods are compared in Figure 6 for the Fromveur Strait at the three locations and in Figure 7 for the Alderney Race at the two locations. The black crosses refer to the linear results (Section 2.2), the blue squares are obtained by the advanced linear method (Section 2.3) whereas the red circles refer to the exponential method (Section 2.4).

The advanced linear method improves the results, since the error never exceeds 9% in the Fromveur Strait whereas

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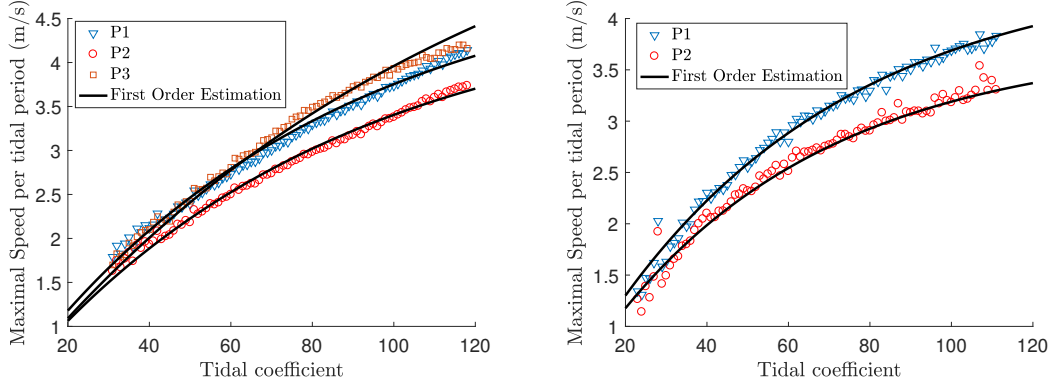


Figure 5: Representation of the peak vector velocity, averaged per tidal coefficient, from numerical computation (Section 2) according to tidal coefficient. The black lines are an exponential approximation of the curve as defined in Equation 2.

Table 3
Coefficients calibration α and β at each locations

Coefficient	P1 Fromveur	P2 Fromveur	P3 Fromveur	P1 Alderney	P2 Alderney
α	5.17	4.73	6.77	3.77	4.51
β	77.20	78.66	113.60	53.44	58.84

the linear method reaches 16% for exceptional spring tidal conditions. The error remains high for exceptional neap tidal conditions and reaches 9% in the Fromveur Strait.

Figures 6 and 7 highlight that the exponential method considerably improves predictions of current magnitude. The linear method applied in the Alderney Race presents error around 80% with the same trend as in the Fromveur Strait. The advanced linear method particularly improves results for tidal coefficients c include between 45 and 95. The exponential method can improve results for very low tidal range ($c < 35$), since the error changed from 80% to 19% in the Alderney Race. For $c > 35$ the maximal error is 4.5% in the Alderney Race. This method improves the results, particularly for extreme tidal range.

Table 4 shows the mean error of the three methods performed at the three locations in the Fromveur Strait, and the two locations in the Alderney Race.

It clearly appears that the piece-wise linear function is more efficient than the linear function. The advanced lin-

ear model is less accurate for exceptional neap flows than the exponential method. However, for tidal range included between $c = 45$ and $c = 95$, this advanced linear model is more accurate than the other methods. In short, for exceptional neap tides, the advanced linear and the exponential methods improve significantly the results.

Nevertheless, at exceptional neap tide conditions ($c < 40$), the error remains higher than for other tide conditions whatever the considered method. This is partly due to the high standard deviation of the current velocity at exceptional neap tides (i.e. different peak velocities can be obtained for a given tidal coefficient). This dispersion results from current variability and it cannot be taken into account in the methods suggested. However, such tidal conditions are associated with limited tidal turbine production. Thus, it has a limited impact on the annual energy production. In addition, when the turbine is not running because of low current velocities, it does not need any adjustments.

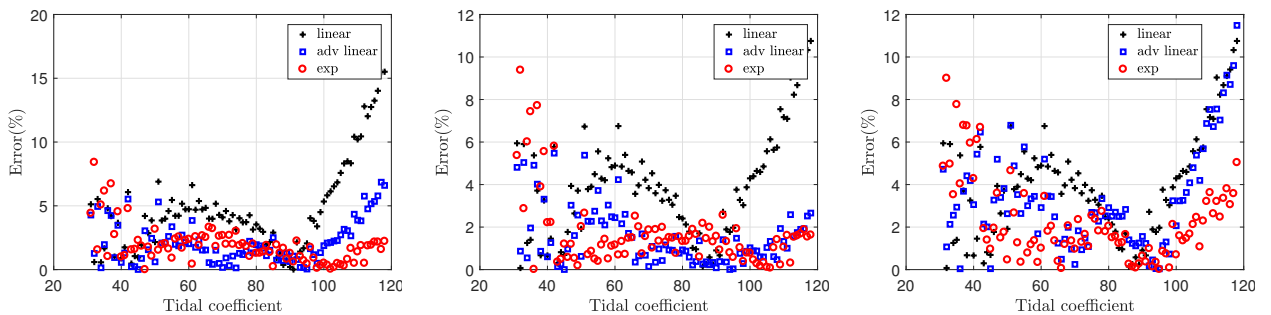


Figure 6: Absolute errors compared to reference values at the three locations P1, P2 and P3 in the Fromveur Strait, for linear, advanced linear and exponential methods.

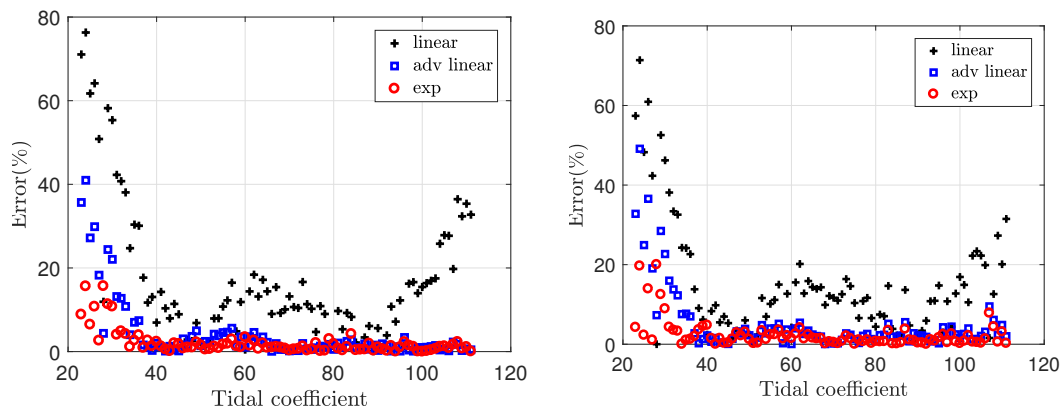


Figure 7: Absolute errors compared to reference values at the two locations P1 and P2 in the Alderney Race, for linear, advanced linear and exponential methods.

Table 4

Comparison of the mean error for the different methods used, at all locations.

Method	P1 Fromveur	P2 Fromveur	P3 Fromveur	P1 Alderney	P2 Alderney
Linear	4.7%	3.9%	5.8%	17.0%	14.8%
Advanced linear	2.2%	1.5%	3.3%	4.3%	5.2%
Exponential	1.9%	1.7%	2.3%	2.1%	2.4%

4. Conclusion

In this study, three methods to compute tidal current velocity vector from tidal range data have been presented and compared. The methodology has been applied to two tidal stream energy sites. The reference values are based on a depth-averaged current velocity computed with regional hydrodynamic models simulating the tidal propagation. The first method presented is a linear approximation which relies on reference velocity vectors at typical tidal periods of mean spring and neap conditions to compute current velocities. The second method is an improvement of the first one and consists in a piece-wise linear function. It requires three reference velocity vectors corresponding to tidal coefficients equal to 45, 70 and 95, respectively. This corrected model is composed of two linear approximations that improve the precision of the model. A third method corrects the linear function with a coefficient computed thanks to an exponential relation between tidal range and velocity.

The three methods have been tested at three different locations in the Fromveur Strait, and two locations in the Alderney Race, and compared to reference values of current velocities. The three methods provide comparable results in terms of tidal current velocity. In exceptional neap and spring conditions, the advanced method overestimates the velocity. The exponential method improves the accuracy during neap tides.

To conclude, the piece-wise linear method and the exponential method are efficient tools to predict tidal current velocities. In a tidal turbines farm project, these methods can be implemented to anticipate the settings of yaw system turbines, or compute in a simple manner the optimum power

production. It allows a very fast estimation of tidal currents with few data.

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