



Swansea University  
Prifysgol Abertawe



## Cronfa - Swansea University Open Access Repository

---

This is an author produced version of a paper published in:  
*Renewable Energy*

Cronfa URL for this paper:  
<http://cronfa.swan.ac.uk/Record/cronfa50672>

---

### **Paper:**

Togneri, M., Pinon, G., Carlier, C., Choma Bex, C. & Masters, I. (2019). Comparison of synthetic turbulence approaches for blade element momentum theory prediction of tidal turbine performance and loads. *Renewable Energy*  
<http://dx.doi.org/10.1016/j.renene.2019.05.110>

---

This item is brought to you by Swansea University. Any person downloading material is agreeing to abide by the terms of the repository licence. Copies of full text items may be used or reproduced in any format or medium, without prior permission for personal research or study, educational or non-commercial purposes only. The copyright for any work remains with the original author unless otherwise specified. The full-text must not be sold in any format or medium without the formal permission of the copyright holder.

Permission for multiple reproductions should be obtained from the original author.

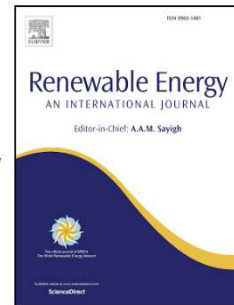
Authors are personally responsible for adhering to copyright and publisher restrictions when uploading content to the repository.

<http://www.swansea.ac.uk/library/researchsupport/ris-support/>

# Accepted Manuscript

Comparison of synthetic turbulence approaches for blade element momentum theory prediction of tidal turbine performance and loads

Michael Togneri, Grégory Pinon, Clément Carlier, Camille Choma Bex, Ian Masters



PII: S0960-1481(19)30783-9  
DOI: <https://doi.org/10.1016/j.renene.2019.05.110>  
Reference: RENE 11702

To appear in: *Renewable Energy*

Received Date: 12 December 2018  
Revised Date: 8 May 2019  
Accepted Date: 26 May 2019

Please cite this article as: Togneri M, Pinon Gré, Carlier Clé, Choma Bex C, Masters I, Comparison of synthetic turbulence approaches for blade element momentum theory prediction of tidal turbine performance and loads, *Renewable Energy* (2019), doi: <https://doi.org/10.1016/j.renene.2019.05.110>.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

# Comparison of synthetic turbulence approaches for blade element momentum theory prediction of tidal turbine performance and loads

Michael Togneri<sup>a,\*</sup>, Grégory Pinon<sup>b</sup>, Clément Carlier<sup>c</sup>, Camille Choma Bex<sup>c</sup>, Ian Masters<sup>a</sup>

<sup>a</sup>*College of Engineering, Swansea University, Singleton Park, Swansea, SA2 8PP, UK*

<sup>b</sup>*Normandie Université, UNIHAVRE, CNRS, LOMC, 7600 Le Havre, France*

<sup>c</sup>*IFREMER, 150 Quai Gambetta, 62200 Boulogne s/ Mer, France*

---

## Abstract

Turbulence is a crucial flow phenomenon for tidal energy converters (TECs), as it influences both the peak loads they experience and their fatigue life. To best mitigate its effects we must understand both turbulence itself and how it induces loads on TECs. To that end, this paper presents the results of blade element momentum theory (BEMT) simulations of flume-scale TEC models subjected to synthetic turbulent flows. Synthetic turbulence methods produce three-dimensional flowfields from limited data, without solving the equations governing fluid motion. These flowfields are non-physical, but match key statistical properties of real turbulence and are much quicker and computationally cheaper to produce. This study employs two synthetic turbulence generation methods: the synthetic eddy method and the spectral Sandia method. The response of the TECs to the synthetic turbulence is predicted using a robust BEMT model, modified from the classical formulation of BEMT. We show that, for the cases investigated, TEC load variability is lower in stall operation than at higher tip speed ratios. The variability of turbine loads has a straightforward relationship to the turbulence intensity of the inflow. Spectral properties of the velocity field are not fully reflected in the spectra of TEC loads.

---

\*Corresponding author

Email address: M.Togneri@swansea.ac.uk (Michael Togneri)

*Keywords:* BEMT, SEM, Sandia, tidal turbines, turbulence, simulation

## 1. Introduction

Turbulence is a significant concern for tidal energy converters (TECs), due to its importance in determining the fluctuating loads on turbine blades [1] and ultimately the fatigue life of the device and its components [2]. Studies have measured a variety of different parameters for characterising turbulence at real sites [3, 4, 5, 6], but there is no absolute consensus on exactly which characteristics are the most important for prediction of TEC loads. Nonetheless, it is standard to make use of some measure of turbulence strength (such as turbulent kinetic energy,  $k$ , or turbulence intensity, TI) and some measure of the spatial extent of turbulent fluctuations, typically as integral length scale [1]. Translating turbulence to turbine loads is also an area of ongoing research: there have been several experimental and computational investigations that have examined the influence of turbulence on TECs or scaled-down TEC models (see for instance [7, 8, 9]).

This paper will present results from blade element momentum theory (BEMT) simulations of a flume-scale tidal turbine model. BEMT is a well-established method of simulating horizontal-axis turbines that extract energy from a flowing fluid [10]; its simplicity means that it is capable of simulating far more cases in the same amount of time than other numerical approaches that model flow physics more completely. The BEMT model used here is a robust code developed at Swansea University that incorporates a number of modifications to classical BEMT theory [11, 12]. Most significantly, for the purpose of simulating TEC response to turbulent flows, it is capable of incorporating unsteady, non-uniform inflow conditions [13].

A modeller of turbulence can choose to deal with the fluid physics in greater or lesser detail [14]. The most sophisticated turbulence models have significant



predictive power and correspondingly require a great deal of computational re-  
source [15], but for this study it is important to select an approach that reflects  
30 the strengths of BEMT itself: its ability to quickly investigate a wide range of  
flow cases and operating conditions. This ability loses its value if it is necessary  
to perform a computationally-expensive calculation to generate turbulent inflow  
condition before the TEC's response to those conditions can be simulated. This  
35 motivates the use of synthetic turbulence methods, which use a restricted set of  
parameters to generate a three-dimensional turbulence velocity flowfield. These  
characteristic parameters are typically the velocity covariances or the spectra,  
both of which can be obtained with conventional instrumentation in the field  
with a high degree of confidence [16]. A flowfield generated this way does not,  
40 in general, satisfy the governing equations of fluid motions and is therefore not  
a physically accurate representation of turbulence, but it does replicate certain  
statistical parameters of turbulence.

This study compares two synthetic turbulence approaches. The first is the  
45 synthetic eddy method (SEM), which approximates turbulence as a collection  
of randomly-placed 'eddies'. This was originally developed to generate inflow  
conditions for large eddy simulations, and has been used in this context to  
simulate loads and wakes for both wind and tidal turbines [17, 18]. We also  
synthesise turbulence with a spectral method, which we also refer to as the  
50 Sandia method after Sandia National Laboratories where it was first developed  
[19]; this method, or a similar one, is implemented in commercial codes such as  
*Tidal Bladed* and open-source codes like NREL's *TurbSim* [20]. Details of these  
schemes are given in sections 2.3 and 2.4.

55 We begin with a brief description of the BEMT model used, and then introduce  
the specific lab-scale TEC that is simulated in this study and the conditions in  
which it is operated. This is followed by a brief discussion of the methods used  
to generate synthetic turbulence, and an assessment of how well they are able  
to replicate turbulent properties. We then go on to examine the results of using

60 these synthetic turbulent flowfields in terms of power and thrust coefficients, as well as distributed loads across turbine blades.

## 2. Background

### 2.1. Blade element momentum theory model

Blade element momentum theory (BEMT) is a well-established model of  
65 conventional horizontal-axis rotors that was originally developed in the 1930s for aircraft propellers [21], but is still used today for both wind [22] and tidal [23] turbine applications. Its basic principle is to determine the fluid dynamic forces on a rotor through the necessary equality of its role as a source/sink of axial and swirl momentum with the lift and drag forces on the blade sections.  
70 The specific BEMT model employed in this study is a well-validated, robust code developed at Swansea [11, 12] that uses an iterative constrained nonlinear optimiser to minimise the difference between these two analyses of the rotor. This difference is quantified by the parameters called ‘induction factors’ which are a non-dimensional measure of the change in axial and swirl velocity induced  
75 by the presence of the rotor; the solver is considered to have converged on a solution when the change in induction factor from one iteration to the next is less than the tolerance of  $1 \times 10^{-6}$ . This BEMT model also incorporates a quasi-unsteady inflow model, allowing simulation of a turbine in unsteady, non-uniform flow conditions.

### 80 2.2. Case study

We compare our BEMT predictions to a lab-scale turbine that has been extensively investigated at the IFREMER combined wave and current flume [24]. The turbine is a three-bladed design of 0.7m diameter; its chord and twist distributions are shown in figure 1. A NACA 63418 section was used across the  
85 entire radius.

The experimental study reported in [24] investigated a wide range of flow conditions, but in the current paper we restrict ourselves to two of these cases,

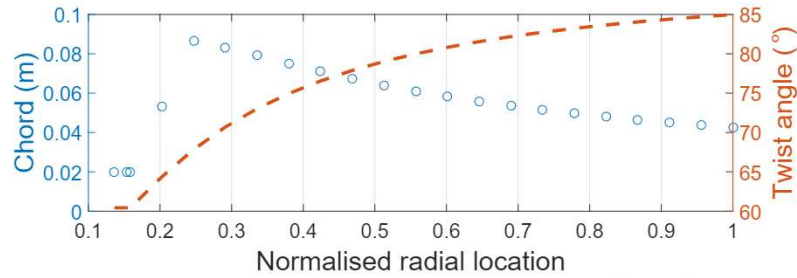


Figure 1: Radial chord and twist distributions for the rotor used in the case study. Twist is defined as the angle between the chord line and the axis of rotation.

which we call ‘low turbulence’ and ‘high turbulence’. In both cases, the mean  
 90 flow velocity is  $1 \text{ ms}^{-1}$ , and the only mean flow property that changes is the tur-  
 bulence intensity (TI), denoted  $I_\infty$ . This is the ratio of the root mean square of  
 the fluctuation velocity components to the mean velocity magnitude, expressed  
 as a percentage. If we write the Cartesian components of the velocity field as  
 $u, v, w$ , and use  $u', v', w'$  to denote their fluctuation components, then TI can  
 95 be defined as:

$$TI = 100 \sqrt{\frac{\frac{1}{3}(\langle u'^2 \rangle + \langle v'^2 \rangle + \langle w'^2 \rangle)}{\langle u \rangle^2 + \langle v \rangle^2 + \langle w \rangle^2}}, \quad (1)$$

where angle brackets are used to denote time-averaged values. The ‘low tur-  
 bulence’ case has a turbulence intensity of  $I_\infty = 3\%$ ; the ‘high turbulence’ case  
 has  $I_\infty = 15\%$ . In addition to TI we also characterise turbulence through its  
 anisotropy ratio - that is, the relative magnitude of turbulent fluctuations in  
 100 each direction. This was not directly measured in the flume study, but based  
 on the theoretical predictions of Nezu and Nakagawa [25], which were later cor-  
 roborated by field measurements taken by Milne *et al.* [4]. We assume that this  
 ratio takes the value  $\sigma_u : \sigma_v : \sigma_w = 1 : 0.75 : 0.56$ , where  $\sigma_u$  represents the stan-  
 dard deviation of the  $u$ -component of velocity and is calculated as  $\sigma_u = \langle u'^2 \rangle^{\frac{1}{2}}$ .  
 105 Flume data on the integral lengthscale is not available; to strike a balance be-  
 tween loading due to rotor-scale fluctuations and loading due to chord-scale  
 fluctuations, integral lengthscale was set to 40% of the turbine radius.

In order to verify that our BEMT model is able to accurately capture the mean  
110 turbine performance, we simulate the turbine in plug flow over a range of tip  
speed ratio (TSR) values to obtain the conventional performance curves of power  
and thrust coefficients,  $C_P$  and  $C_T$ . Lift and drag data for the NACA 63418  
section were taken from Abbott and Doenhoff [26], corresponding to a Reynolds  
number of  $6 \times 10^6$ . Comparisons of these results with flume measurements are  
115 shown in figure 2. We see that there is very good agreement in the power  
coefficient across the entire TSR range, but due to the additional measured  
drag from the support structure the model's prediction of thrust coefficient are  
consistently lower than the measured values. An approximate correction for  
this can be made by treating the support structure as a simple cylinder that is  
120 partially immersed in the turbine wake, calculating the resultant drag and sub-  
tracting this from the measured results. This correction substantially improves  
the agreement between predicted and measured results, particularly for the low  
turbulence case. To test the sensitivity of the results to the rotor discretisation,  
a second simulation was performed with almost twice as many radial elements,  
125 going from 22 to 43 evenly-spaced elements per blade. The consequent change  
in performance was approximately 1%, which was sufficiently small to conclude  
that results obtained with the coarser discretisation would be satisfactory.

### 2.3. Synthetic eddy method

The synthetic eddy method was originally developed by Jarrin *et al.* as a  
130 means of generating inflow conditions for large eddy simulations (LES) of fluid  
flow [27], and continues to see use in this role [28]. Its basic approach is to fill  
a volume of space with randomly-positioned 'eddies' that induce a velocity in  
their own vicinity. Each 'eddy' is defined by a shape function (for the current  
study, a compactly-supported tent function), a size based on the specified in-  
135 tegral lengthscale, and a strength. By calculating appropriate values for these  
properties based on measurements from real flows (e.g., turbulent kinetic en-  
ergy, anisotropy ratios, integral lengthscales etc.), the flowfield induced by the



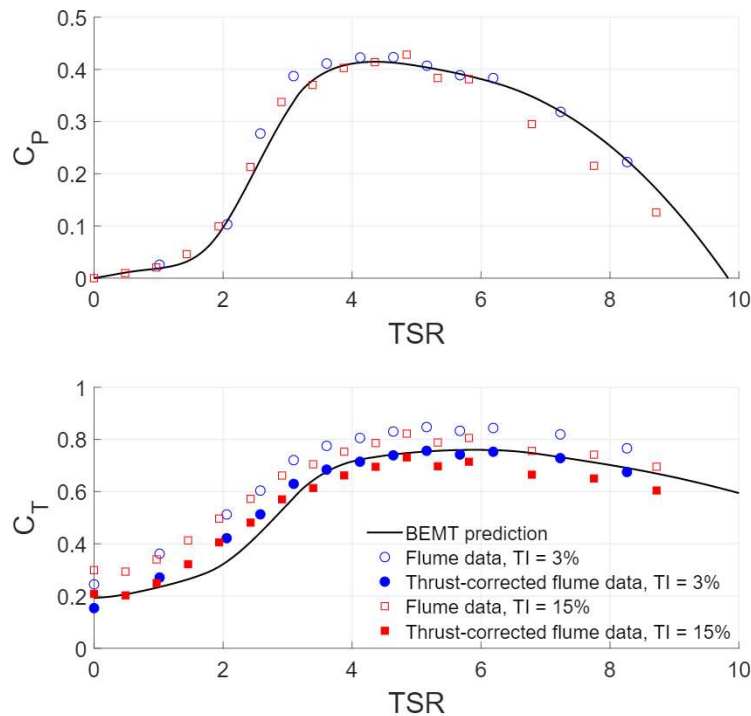


Figure 2: Power and thrust coefficient dependence on TSR. Flume data are taken from Mycek *et al.* [24]. Filled symbols (for thrust only) indicate flume data corrected for the presence of the support structure, as described in the text. Experimental data points represent a time-average value over 100s of measurement.

eddies will have, statistically, the same Reynolds stress tensor as the real flow-field it is based on. A full description of the underlying mathematics can be  
 140 found in [29]. It is important to bear in mind that, despite the name ‘eddy’, these velocity disturbances are not realistic representations of physical eddies and indeed are not intended to be; for clarity, we refer to them as pseudo-eddies.

#### 2.4. Sandia method

145 The Sandia approach is a spectral method that was developed to simulate complete wind flowfields from a restricted set of measured data [19]; applying it



to tidal stream flowfields is an intuitive extension of its original design purpose. The basis of the Sandia method is an array  $\mathbf{S}$  whose every entry contains a power spectral density (PSD) corresponding to a pair of points. In this array, each diagonal entry corresponds to an auto-PSD, and each off-diagonal to a cross-PSD. We perform a Cholesky decomposition to define a matrix  $\mathbf{H} : \mathbf{S} = \mathbf{H}\mathbf{H}^{*T}$ ; then, by applying a random phase to each entry of  $\mathbf{H}$ , summing along the  $n$ th row will yield a series of Fourier coefficients corresponding to the  $n$ th point. These coefficients define a discrete spectrum which, when transformed back into the time domain, results in a time series of velocity with the correct spectral properties and spatial cross-correlations with all other points.

A key strength of the Sandia method is that it can work with any arbitrary spectrum, measured or theoretical. Observations have shown that turbulent flowfields in strong tidal currents tend to be well-described by the von Kármán spectrum[4], so this is employed here. In the absence of specific data on cross-spectra, Veers *et al.* [19] proposed a coherence function that relates the cross-PSD between any two points to their respective auto-PSDs and their separation distance, and we apply this approach here. Note that when generating a synthetic flowfield of finite duration, the spectrum is truncated compared to its theoretical value, resulting in a loss of energy. To mitigate this, we scale the finite time series according to the Rayleigh theorem to ensure that its power matches that of the full PSD. Lastly, an important shortcoming of the method is that each component of velocity is generated independently, which means that all cross-component correlations will be zero.

### 3. Synthetic turbulence validation

Before using the synthetic turbulent flowfields as inflow conditions to a BEMT model, we first verify that they are behaving as expected. We use flow conditions from the IFREMER flume tank experiments [24] as a benchmark for the synthetic turbulence methods. For all synthetic flowfields, the domain was

## ACCEPTED MANUSCRIPT

Table 1: Mean values and standard deviations of turbulence intensity ( $I_\infty$ ) and anisotropy ratio  $\sigma_u : \sigma_v : \sigma_w$  for the SEM and Sandia methods compared to the benchmark turbulent flow cases

	$I_\infty$	$\sigma_u : \sigma_v : \sigma_w$
<b>Target</b>	3%	1 : 0.75 : 0.56
SEM	$2.97 \pm 0.03\%$	$1 \pm 0.01 : 0.749 \pm 0.008 : 0.557 \pm 0.008$
Sandia	$3.00 \pm 0.05\%$	$1 \pm 0.01 : 0.747 \pm 0.010 : 0.557 \pm 0.005$
<b>Target</b>	15%	1 : 0.75 : 0.56
SEM	$14.8 \pm 0.1\%$	$1 \pm 0.03 : 0.750 \pm 0.012 : 0.558 \pm 0.013$
Sandia	$15.1 \pm 0.2\%$	$1 \pm 0.02 : 0.744 \pm 0.013 : 0.553 \pm 0.012$

defined as extending 10m in the longitudinal direction, corresponding to 10s of flow for a mean flow speed of  $1\text{ms}^{-1}$ . The vertical and lateral extents of the synthetic flowfields were set to 1.5 times the diameter  $D$  of the rotor (cf. the discussion of the turbine geometry in section 2.2). The grid spacing was  $0.075D$  in the lateral and vertical directions, and a timestep of 0.01 seconds was chosen for the longitudinal direction, equivalent to a grid spacing of  $0.0143D$ . One hundred independent realisations of the turbulent flow were generated for both the high and low turbulence conditions with both synthetic turbulence methods. In table 1, we present the  $I_\infty$  and anisotropy ratios for these benchmark flows. To obtain these data, we calculate a single mean value and standard deviation of both TI and anisotropy ratio for each flowfield realisation, then tabulate the average of these across all realisations.

The synthetic turbulence methods are clearly able to satisfactorily replicate the key turbulence parameters of the benchmark turbulence cases. It is also instructive, however, to examine the spectral properties of the synthetic flowfields, and these are shown in figure 3. The Sandia method recovers the theoretical von Kármán spectrum far more accurately than SEM; this is unsurprising, as the Sandia method should replicate the spectrum used as a template. What is interesting is the manner in which SEM fails to accurately reproduce the expected

PSD. Lower frequencies, corresponding to larger-scale motions, are relatively well-captured. However, as we move towards the frequencies comprising the inertial subrange, the PSD of the SEM turbulence exceeds the PSD of the von Kármán spectrum in magnitude for a narrow frequency range, approximately 1-4 Hz. At frequencies above this range, the magnitude of the PSD drops sharply below that of the template spectrum, and from around 10 Hz upwards exhibits a series of linearly-spaced ‘fringes’. These fringes closely approximate a  $\text{sinc}^4$  function, which is the PSD of a single tent function; the slight ‘fuzziness’ of the peaks in the SEM spectra is due to the fact that this PSD results from the superposition of several tent functions distributed randomly in three dimensions.

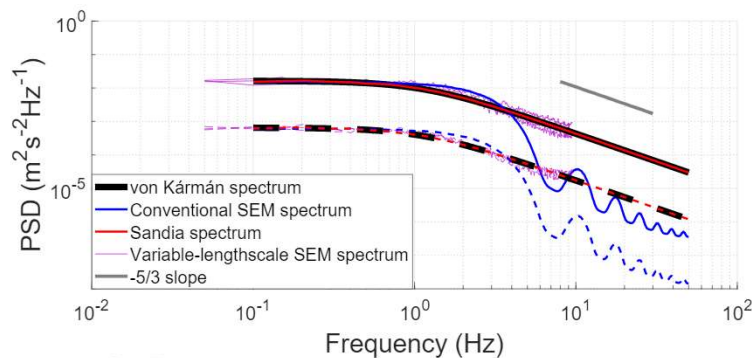


Figure 3: Comparison of von Kármán spectrum and spectra from flowfields generated using the two synthetic turbulence models. Three SEM cases with variable lengthscales are shown in purple, as explained in text. Solid lines shows high-turbulence case and dashed lines show low-turbulence case.

This non-physical behaviour of the SEM spectra at high frequencies can be ameliorated by varying the lengthscale of the pseudo-eddies [30]. The purple lines in figure 3 represent PSDs from SEM flowfields whose eddy lengthscales are governed by a normal distribution; the three different cases represent length-scale distributions whose standard deviations are 25%, 50% and 75% of the mean value - lengthscales below zero are not permitted. Although modifying

the SEM in this way means that the resultant flow does not strictly satisfy the mathematical conditions of the original formulation, the non-zero components  
215 of the Reynolds stress tensor of the resultant flowfields are still equal to those of the template data to within a standard deviation. Flowfields generated with modified SEM had a duration of 20s and a timestep of 0.0525s; this is the reason their spectra exist over a different frequency range to the Sandia and conventional SEM results.

220

#### 4. Results

The effects of the low and high turbulence flows on the test turbine are examined for three different operating conditions: at power optimum (corresponding to a steady state characterised by  $TSR = 4.4$ ,  $C_P = 0.4121$ ,  $C_T = 0.7418$ ),  
225 in partial stall ( $TSR = 2.5$ ,  $C_P = 0.2141$ ,  $C_T = 0.4326$ ) and in an overspeed condition ( $TSR = 8$ ,  $C_P = 0.2316$ ,  $C_T = 0.7230$ ). A simplified control scheme kept the rotor at a fixed TSR relative to the mean flow velocity. The results of these simulations are tabulated in table 2 and presented graphically in figure 4. Analogous to the case in the validation results presented in section 3, the  
230 numbers shown here are calculated by taking the mean coefficients from simulations of the turbine response to each of the hundred independent realisations of each turbulent case, and calculating the mean and standard deviations of those populations. Note also that both thrust and power coefficients are normalised against the mean flow velocity for the whole simulation duration, rather than  
235 the instantaneous flow velocity at hub height.

These results illustrate several important phenomena. Firstly, none of the turbulent cases investigated resulted in a significant shift of the mean load characteristics. In every case, the mean load coefficients were within a single standard deviation of the corresponding steady state values. Secondly, the variability  
240 of the mean load coefficients appears to be related very straightforwardly to



## ACCEPTED MANUSCRIPT

Table 2: Mean value and standard deviations of power and thrust coefficients from BEMT simulations

Stall region (TSR = 2.5, steady $C_P = 0.2140$ , steady $C_T = 0.4326$ )			
Turbulence model	TI	$C_P$	$C_T$
<b>SEM</b>	3%	$0.2114 \pm 0.0035$	$0.4351 \pm 0.0057$
	15%	$0.1987 \pm 0.0188$	$0.4359 \pm 0.0326$
<b>Sandia</b>	3%	$0.2117 \pm 0.0026$	$0.4351 \pm 0.0055$
	15%	$0.2021 \pm 0.0145$	$0.4397 \pm 0.0312$
Optimal region (TSR = 4.4, steady $C_P = 0.4121$ , steady $C_T = 0.7418$ )			
Turbulence model	TI	$C_P$	$C_T$
<b>SEM</b>	3%	$0.4129 \pm 0.0203$	$0.7421 \pm 0.0208$
	15%	$0.4318 \pm 0.0942$	$0.7403 \pm 0.0955$
<b>Sandia</b>	3%	$0.4175 \pm 0.0216$	$0.7474 \pm 0.0225$
	15%	$0.4276 \pm 0.1027$	$0.7425 \pm 0.1055$
Overspeed region (TSR = 8, steady $C_P = 0.2316$ , steady $C_T = 0.7230$ )			
Turbulence model	TI	$C_P$	$C_T$
<b>SEM</b>	3%	$0.2326 \pm 0.0257$	$0.7242 \pm 0.0274$
	15%	$0.2631 \pm 0.1341$	$0.7428 \pm 0.1400$
<b>Sandia</b>	3%	$0.2324 \pm 0.0277$	$0.7242 \pm 0.0297$
	15%	$0.2525 \pm 0.1400$	$0.7375 \pm 0.1493$

the turbulence intensity: moving from low turbulence to high turbulence (i.e., a fivefold increase from  $I_\infty = 3\%$  to  $I_\infty = 15\%$ ) also causes the standard deviation of the mean load coefficient to increase by a factor of approximately 5 - more precisely, the factor of proportionality varies in the range 4.6-5.8. This increase

245



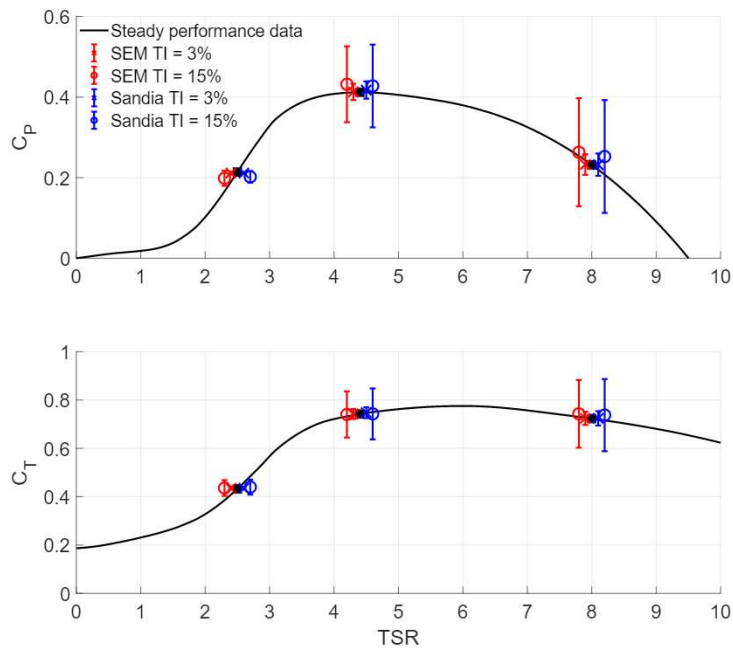


Figure 4: Power and thrust coefficients for turbulent simulations, compared to performance curves for steady flow. Black squares indicate the steady stall, optimum and overspeed operating cases; coloured markers show mean coefficient values for turbulent cases with error bars indicating standard deviation. Turbulent data are offset in TSR for clarity.

is roughly twice as large as that seen in the experiment of Mycek *et al.*, whose results indicate that load coefficients increase by a factor of 2.7-2.9 between the low turbulence and high turbulence cases [24].

250 This proportionality is observed for intermediate values of the turbulence intensity as well, as can be seen in figure 5. This figure shows how the turbine power and thrust coefficients in optimum operation change for TI values between the 3% and 15% cases tested above. The mean values of the coefficients are not affected by the turbulence intensity - there is an apparent tendency  
 255 for the mean  $C_P$  value to increase with TI, but the change is not statistically significant. The coefficient standard deviations, however, exhibit a clear linear

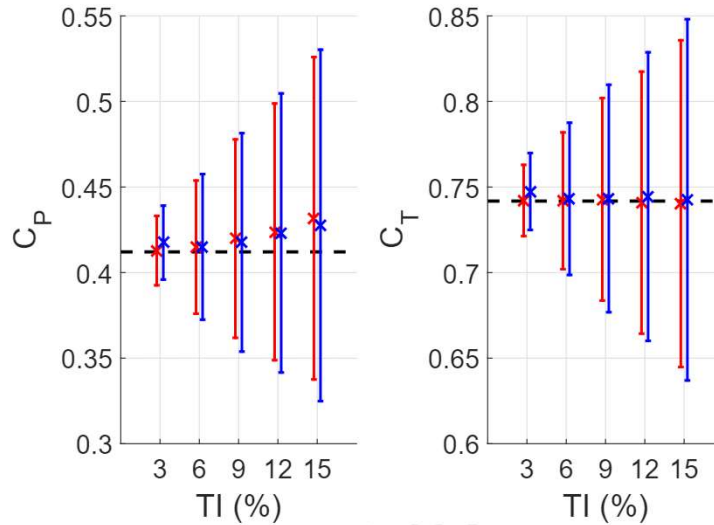


Figure 5: Power and thrust coefficients for simulations of turbine at optimum TSR of 4.4 under a range of turbulent conditions (TI = 3, 6, 9, 12, 15%). Dashed black lines indicate values of power and thrust coefficient in steady flow conditions; crosses and bars indicate coefficient mean values and standard deviations. Results from SEM turbulence are shown in red and those from Sandia turbulence in blue. Note that SEM results are shown with a slight negative offset in TI and Sandia results with a slight positive offset to make it easier to distinguish the results of the different methods, but the actual TI values are as indicated above.

dependence on turbulence intensity. Calculating a linear best fit between TI and standard deviation of the load coefficients shows that the constant of proportionality is 0.9. Section 5 discusses this finding in greater detail.

260

It is also interesting to examine how variability of loads depends on operating conditions. The standard deviation of power and thrust coefficients does not differ greatly between optimum and overspeed operation, but drops significantly when the turbine is operated in the stall range. A similar discrepancy is also  
 265 seen in the experimental results [24]. On the face of it, this is a surprising result: when the turbine is in the stall range (and therefore rotating more slowly), the blade-relative velocities will be more affected by the variations in inflow velocity. The same turbulent fluctuations would lead to greater variability in angle

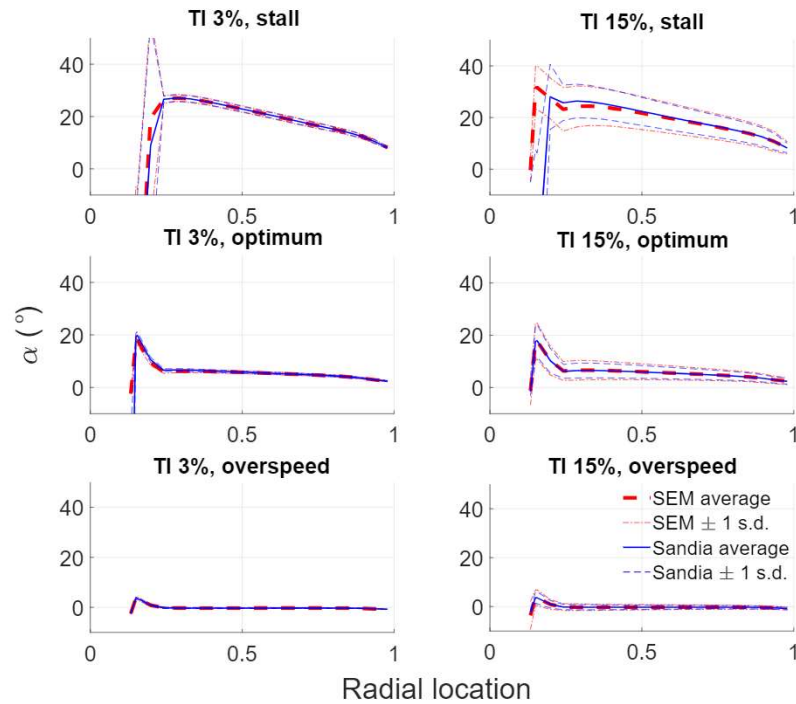


Figure 6: Distributions of angle of attack on turbine blades, averaged across all blades and all runs. Average values are shown as thick lines, in red for SEM turbulence and blue for Sandia turbulence; thinner lines of corresponding colour indicate one standard deviation above and below the average.

of attack; this is confirmed by examination of the angle of attack distributions  
 270 shown in figure 6.

Nevertheless, this wider angle of attack range in stall operation does not  
 lead to a wider range of hydrodynamic forces, as is visualised in more detail  
 in figures 7 and 8, which show the average thrust and in-plane forces per unit  
 275 length across all blades for all operating conditions and turbulence models. The  
 standard deviations of these force distributions show the same tendency to be  
 significantly greater in high-TSR operating conditions as was seen in the whole-  
 turbine load coefficients. The results also make it very clear that the mean force

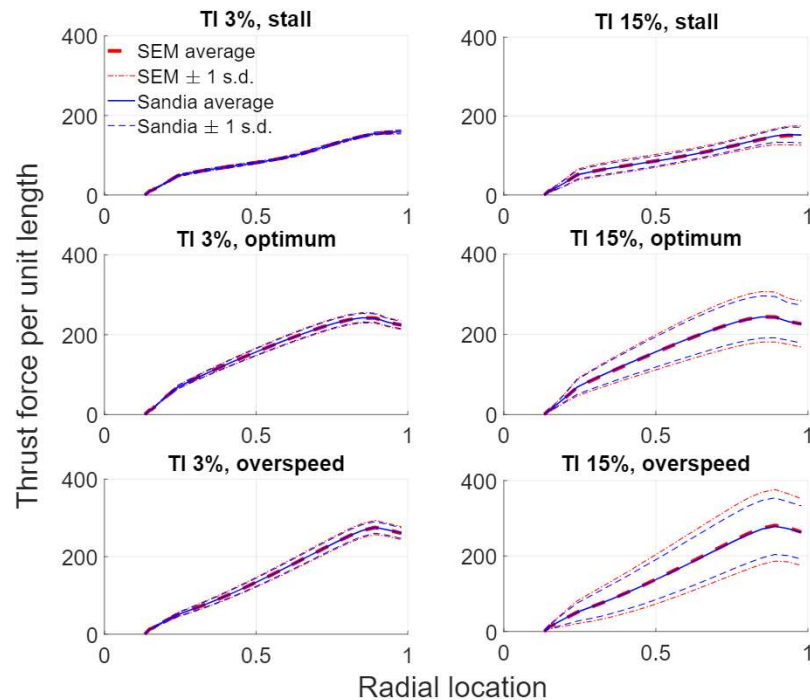


Figure 7: Distributions of thrust force per length on turbine blades, averaged across all blades and all runs. Average values are shown as thick lines, in red for SEM turbulence and blue for Sandia turbulence; thinner lines of corresponding colour indicate one standard deviation above and below the average.

distribution is almost unaffected by the choice of turbulence model. The effect  
 280 on force variability is more significant - particularly in the high turbulence cases  
 we see that the standard deviation of these force distributions is greater with  
 SEM turbulence rather than Sandia turbulence.

In figure 9, we compare the spectral properties of the turbine power output  
 285 and the inflow velocity. There are broad similarities in the shapes of the power  
 and velocity spectra: in particular, we observe that the power spectra for Sandia  
 turbulence cases tend to be greater in magnitude both at the high-frequency  
 end and the extreme low-frequency end, while SEM turbulence yields a greater

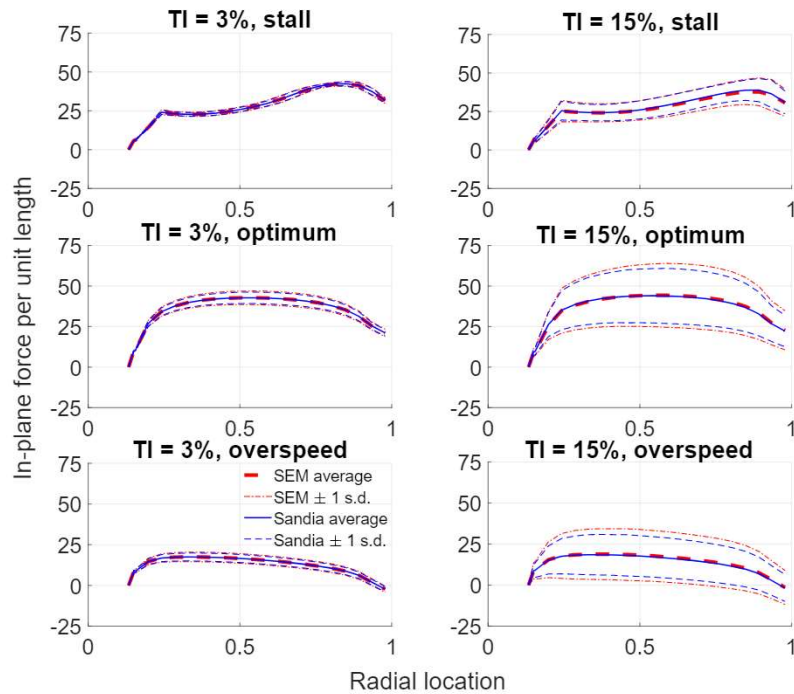


Figure 8: Distributions of in-plane force per length on turbine blades, averaged across all blades and all runs. Average values are shown as thick lines, in red for SEM turbulence and blue for Sandia turbulence; thinner lines of corresponding colour indicate one standard deviation above and below the average.

magnitude in the mid-range, just as is seen in the velocity spectra.

290

As was noted in section 3, modifying the SEM to permit variable lengthscales for the pseudo-eddies improves the spectral behaviour of the resulting synthetic turbulent flowfield. In the right-hand panels of figure 9, the average spectrum from all three of the variable lengthscale SEM cases investigated is plotted in purple alongside the spectra of the conventional synthetic turbulence models. The corresponding spectra of turbine power are plotted in the left-hand panels of the same figure. These spectra are noticeably noisier than those obtained with the Sandia or unmodified SEM turbulence models, but throughout most

295



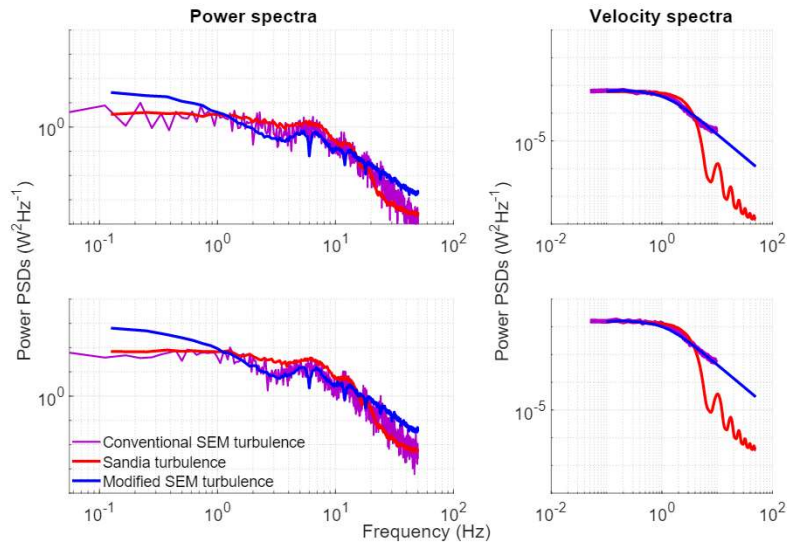


Figure 9: PSDs of rotor power in left-hand panels; right-hand panels show spectra of velocity for comparison. Top panels show results from the low-turbulence case and lower panels show results from the high-turbulence case.

of the frequency range the modified SEM spectra are intermediate between the  
 300 other two cases. Care should be taken in interpreting the behaviour of the  
 power spectra for frequencies above 9.5 Hz. This is the Nyquist frequency for  
 the modified-lengthscale SEM velocity spectra, so the velocity spectrum is not  
 explicitly specified by the input above this threshold.

## 5. Discussion

305 The clearest result from the simulations presented here is the very straight-  
 forward relationship between the turbulence intensity and the resultant standard  
 deviation of the load coefficients. This was suggested by the results shown in  
 table 2 and figure 4 and reinforced by repeating the study for intermediate val-  
 ues of turbulence intensity. This increases our confidence in this observation,  
 310 and allows us to state the relationship more precisely. The slope of a best fit  
 line for normalised TI against normalised load coefficient standard deviations is

between 0.908 and 0.893, depending on which turbulence model and load coefficient is examined. More plainly, this implies that doubling the TI will increase the standard deviation of the load coefficients by a factor of 1.8. This is in excess  
315 of what is seen in the experimental results, which indicated that by doubling TI, the standard deviations would increase by a factor of around 1.45. Nonetheless, the corresponding Pearson correlation coefficients are all in excess of 0.99, so we can be confident that a straightforward linear relationship is appropriate. This is a very promising result for predicting the effects of turbulence on turbine load.

320

To test the robustness of this result, we have repeated the same analysis for a second turbine design. The second turbine we have elected to study is one that has been scaled for a flume study of wake properties [31]. As a result, its power performance is quite different from what is expected in conventional design;  
325 nonetheless, as shown in figure 10, the BEMT code is able to satisfactorily predict its performance in steady flow over a range of TSR values. To test if the relationship between TI and turbine load variability holds for a different turbine, we have simulated this second turbine in optimum conditions ( $TSR = 4.45$ , corresponding to a steady  $C_P = 0.3278$  and  $C_T = 0.8556$ ) at a range of  
330 TI values between 3% and 15%, in the same manner as was done to produce the results of figure 5. The results of these simulations are visualised in figure 11.

The relationship observed is similar, although the slope of the best fit line is not the same as for the IFREMER turbine, and in this case the slope differs for  
335 power and thrust. The constant of proportionality between standard deviation of  $C_P$  and TI is 0.686 if estimated from SEM turbulence, and 0.722 if estimated from Sandia turbulence; for  $C_T$ , the estimated constants of proportionality are 0.839 with SEM turbulence and 0.899 with Sandia turbulence. More importantly, however, they back up the observation that there is a straightforward  
340 linear relationship between turbulence intensity and the standard deviation of the load coefficients: the correlation coefficients for all datasets are again in excess of 0.99. This suggests that although the BEMT simulations have overes-

345 estimated the increase in coefficient variability with TI for the IFREMER turbine compared to experimental data, we are correct to predict a linear relationship between these parameters.

More surprising is that, both here and in the experiments of Mycek *et al.* [24], load variability is less significant in stall operation than near optimum or in overspeed. This is unintuitive for two reasons: first, as mentioned above, in stall operation the rotational speed is low in comparison to the inflow velocity, 350 so turbulent fluctuations will have a greater impact on the angle of attack of any given blade section. Secondly, in this operating condition more of the blade will be operating at angles of attack near stall. Changes in angle of attack are then more likely to mean that the blade will be rapidly switching between 355 stalled and unstalled conditions, which would intuitively lead to greater variability in the overall hydrodynamic loads. Figure 6 shows that angle of attack variability is indeed greater in stall operation; however, when we examine the variability of forces themselves (as in figures 7 and 8), the opposite tendency is seen. We have checked these results by recalculating the thrust and torque of a 360 given blade element from the time series of angle of attack, in conjunction with the matching time series of the blade-relative velocity magnitude and the blade geometry. These recalculations confirm that the observed greater variability of angle of attack in stall operation does in fact correspond to a counterintuitive lower variability in the load coefficients.

365 A possible explanation for this could be found in the gentle stall characteristics of the NACA 63418 blade section used for the IFREMER rotor, as shown in figure 12. This shows that there is no large drop in lift after separation at approximately  $14^\circ$ . Thus, in stall operation, the variability of the forces resulting from the relatively wide angle of attack range is plausibly smaller than that 370 in optimum or overspeed operation.

In figure 3, we compared the PSDs of the synthetic turbulent flowfields with

one another and with the canonical von Kármán spectrum. Unsurprisingly, we  
375 found that the Sandia method does a very good job of replicating the template  
spectrum, while the SEM method does not. The variable-lengthscale modifica-  
tion to the SEM significantly improves the spectral properties of its flowfields.  
Averaging across multiple realisations (as seen in the right-hand panels of figure  
9) smooths out the noisiness of the spectra from individual flowfields and shows  
380 a clear inertial subrange. Nonetheless, this improvement is not fully reflected in  
the spectra of the resulting turbine loads. A direct comparison is difficult, be-  
cause fewer modified SEM cases were run and their spectra are correspondingly  
noisier; however, it appears that the varying the pseudo-eddy lengthscale does  
cause the spectrum of turbine power to shift towards its shape in the Sandia  
385 case, but by a much smaller margin than is seen for the velocity spectra.

This observation suggests that knowledge of the spectral properties of the tur-  
bulent flowfield is not sufficient to predict the spectral properties of the turbine  
loads for synthetic turbulence. This is similar to observations made of turbu-  
390 lent and turbine power spectra made in flume experiments [32], but there is  
an important distinction to be drawn. Experimental results indicate that as  
frequency increases, velocity and power fluctuations become less well correlated  
and so their spectra differ more significantly at higher frequencies. What this  
study shows is that, even where two different synthetic velocity fields have very  
395 similar spectral properties, the concomitant load spectra are not necessarily  
similar.

## 6. Conclusions

We have used two different synthetic turbulence methods to generate in-  
flow conditions for a BEMT model of a lab-scale TEC. Both SEM and the  
400 Sandia spectral model of turbulence are shown to satisfactorily replicate cer-  
tain statistical properties of real turbulent flow in the flume. Furthermore,  
although conventional SEM produces a flowfield whose velocity PSD diverges



significantly from that of real flows, a simple modification to permit variable-lengthscale pseudo-eddies is seen to address this shortcoming quite well. This  
405 modified SEM is not strictly guaranteed to replicate the template statistics as the classical formulation is, but we found that the Reynolds stress tensor does not significantly differ from the template values. The BEMT model has already been extensively validated [10, 11, 12], but the current study demonstrates that it captures the steady flow behaviour of the IFREMER test turbine to a high  
410 standard when compared to flume measurements.

Our simulations using the synthetic turbulence methods to define inflow conditions for the BEMT produced three key results. The most surprising result is that the variability of thrust and power for the turbine when operated at optimum TSR was reduced if the turbine is operated in stall. This runs counter to  
415 the observation that angle of attack variability is greater in stall operation, but we have confirmed that these two observations are consistent with one another. We hypothesise that this unusual result is caused by the gentle stall characteristics of the NACA 63418 section used in the IFREMER turbine.

420 Secondly, our simulations indicate that the variability of turbine loads, as measured by the standard deviation of the power and thrust coefficients, is directly proportional to TI. We calculated that this relationship has a constant of proportionality equal to 0.9, and that its Pearson correlation coefficient is in excess  
425 of 0.99, meaning that a linear relationship is strongly supported by the data. Simulations of a second turbine also supported a linear increase in load variability with TI with a high degree of certainty.

The third key result sheds some light on the spectral properties of TEC loads in  
430 simulations using synthetic turbulence. As mentioned above, the velocity PSD of SEM can be made more realistic with a variable lengthscale modification; however, the spectra of the turbine loads remain dissimilar. We conclude that, for simulations using synthetic turbulence, the spectral properties of the turbine



loads cannot be predicted from knowledge of the corresponding velocity spectra  
435 alone.

### Acknowledgment

The authors acknowledge the financial support of the Welsh Assembly Government and Higher Education Funding Council for Wales through the Sêr Cymru National Research Network for Low Carbon, Energy and Environment.  
440 The work was also supported by the EPSRC-funded projects “Extension of UKCMER Core Research, Industry and International Engagement” (EP/M014738/1) and “SURFTEC” (EP/P008682/1), and the ERDF-funded Interreg Atlantic Area project MONITOR (EAPA.333/2016). Clément Carlier would like to thank the Normandy Regional Council and IFREMER for the financial support  
445 of his Ph.D. grant. Camille Choma Bex acknowledges the financial support of IFREMER for her Ph.D. grant. The authors also would like to thank the CPER-ERDF program NEPTUNE also financed by the Normandy Regional Council. Finally the authors wish to thank the CRIANN (Centre Régional Informatiques et d’Applications Numérique de Normandie) for their available  
450 numerical computation resources.

### References

### References

- [1] I. Milne, A. Day, R. Sharma, R. Flay, The characterisation of the hydrodynamic loads on tidal turbines due to turbulence, *Renewable and Sustainable Energy Reviews* 56 (2016) 851–864.  
455
- [2] F. Elasha, D. Mba, M. Togneri, I. Masters, J. A. Teixeira, A hybrid prognostic methodology for tidal turbine gearboxes, *Renewable Energy* 114 (2017) 1051–1061.

- [3] E. Osalusi, J. Side, R. Harris, Structure of turbulent flow in EMEC's tidal energy test site, *International Communications in Heat and Mass Transfer* 36 (5) (2009) 422–431.
- [4] I. A. Milne, R. N. Sharma, R. G. Flay, S. Bickerton, Characteristics of the turbulence in the flow at a tidal stream power site, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 371 (1985) (2013) 20120196.
- [5] J. Thomson, B. Polagye, V. Durgesh, M. C. Richmond, Measurements of turbulence at two tidal energy sites in Puget Sound, WA, *Oceanic Engineering, IEEE Journal of* 37 (3) (2012) 363–374.
- [6] M. Togneri, I. Masters, Micrositing variability and mean flow scaling for marine turbulence in Ramsey Sound, *Journal of Ocean Engineering and Marine Energy* 2 (1) (2016) 35–46.
- [7] T. Stallard, R. Collings, T. Feng, J. Whelan, Interactions between tidal turbine wakes: experimental study of a group of three-bladed rotors, *Philosophical Transactions of the Royal Society A* 371 (1985) (2013) 20120159.
- [8] T. Blackmore, W. Batten, A. Bahaj, Influence of turbulence on the wake of a marine current turbine simulator, in: *Proc. R. Soc. A, Vol. 470, The Royal Society*, 2014, p. 20140331.
- [9] P. Pyakurel, J. H. VanZwieten, M. Dhanak, N. Xiros, Numerical modeling of turbulence and its effect on ocean current turbines, *International Journal of Marine Energy* (2017).
- [10] I. Masters, A. Williams, T. N. Croft, M. Togneri, M. Edmunds, E. Zangiabadi, I. Fairley, H. Karunarathna, A comparison of numerical modelling techniques for tidal stream turbine analysis, *Energies* 8 (8) (2015) 7833–7853.
- [11] I. Masters, J. Chapman, J. Orme, M. Willis, A robust blade element momentum theory model for tidal stream turbines including tip and hub loss

- corrections, *Proceedings of IMarEST-Part A-Journal of Marine Engineering and Technology* 10 (1) (2011) 25–35.
- [12] J. C. Chapman, I. Masters, M. Togneri, J. A. C. Orme, The Buhl correction factor applied to high induction conditions for tidal stream turbines, *Renewable Energy* 60 (2013) 472–480.
- [13] M. Togneri, I. Masters, G. Pinon, C. Carlier, C. Choma Bex, Comparison of synthetic turbulence approaches for two numerical tidal turbine models, in: *12th European Wave and Tidal Energy Conference (EWTEC 2017)*, 2017.
- [14] S. B. Pope, *Turbulent flows* (2001).
- [15] P. Moin, K. Mahesh, Direct numerical simulation: a tool in turbulence research, *Annual Review of Fluid Mechanics* 30 (1) (1998) 539–578.
- [16] M. Togneri, M. Lewis, S. Neill, I. Masters, Comparison of ADCP observations and 3D model simulations of turbulence at a tidal energy site, *Renewable Energy* (2017). doi:10.1016/j.renene.2017.03.061.
- [17] I. Afgan, J. McNaughton, S. Rolfo, D. Apsley, T. Stallard, P. Stansby, Turbulent flow and loading on a tidal stream turbine by les and rans, *International Journal of Heat and Fluid Flow* 43 (2013) 96–108.
- [18] A. Creech, W.-G. Früh, A. E. Maguire, Simulations of an offshore wind farm using large-eddy simulation and a torque-controlled actuator disc model, *Surveys in Geophysics* 36 (3) (2015) 427–481.
- [19] P. S. Veers, Three-dimensional wind simulation, Tech. rep., Sandia National Labs., Albuquerque, NM (USA) (1988).
- [20] J. Jonkman, L. Kilcher, *TurbSim User's Guide: Version 1.06.00*, Tech. rep., National Renewable Energy Laboratory (2012).
- [21] H. Glauert, Airplane propellers, in: *Aerodynamic theory*, Springer, 1935, pp. 169–360.

- [22] S. Liu, I. Janajreh, Development and application of an improved blade  
515 element momentum method model on horizontal axis wind turbines, *International Journal of Energy and Environmental Engineering* 3 (1) (2012) 30.
- [23] W. M. J. Batten, A. S. Bahaj, A. F. Molland, J. R. Chaplin, The prediction  
520 of the hydrodynamic performance of marine current turbines, *Renewable Energy* 33 (5) (2008) 1085–1096.
- [24] P. Mycek, B. Gaurier, G. Germain, G. Pinon, E. Rivoalen, Experimental  
study of the turbulence intensity effects on marine current turbines behaviour. part i: One single turbine, *Renewable Energy* 66 (2014) 729–746.
- [25] I. Nezu, H. Nakagawa, *Turbulence in open-channel flows*, Taylor & Francis,  
525 1993.
- [26] I. Abbott, A. von Doenhoff, *Theory of wing sections, including a summary  
of airfoil data*, Courier Corporation, 1959.
- [27] N. Jarrin, S. Benhamadouche, D. Laurence, R. Prosser, A synthetic-eddy-  
530 method for generating inflow conditions for large-eddy simulations, *International Journal of Heat and Fluid Flow* 27 (4) (2006) 585–593.
- [28] K. Wilcox, J. Zhang, I. McLeod, A. Gerber, T. Jeans, J. McMillan, A. Hay,  
R. Karsten, J. Culina, Simulation of device-scale unsteady turbulent flow  
in the fundy tidal region, *Ocean Engineering* 145 (2017) 59–76.
- [29] N. Jarrin, Synthetic inflow boundary conditions for the numerical simulation  
535 of turbulence (2008).
- [30] C. Carlier, Simulation du comportement d'hydroliennes : modélisation de  
l'influence de la turbulence ambiante et des effets d'interaction (2017).
- [31] T. Stallard, T. Feng, P. Stansby, Experimental study of the mean wake  
540 of a tidal stream rotor in a shallow turbulent flow, *Journal of Fluids and Structures* 54 (2015) 235–246.



- [32] O. D. Medina, F. G. Schmitt, R. Calif, G. Germain, B. Gaurier, Turbulence analysis and multiscale correlations between synchronized flow velocity and marine turbine power production, *Renewable Energy* 112 (2017) 314–327.

ACCEPTED MANUSCRIPT



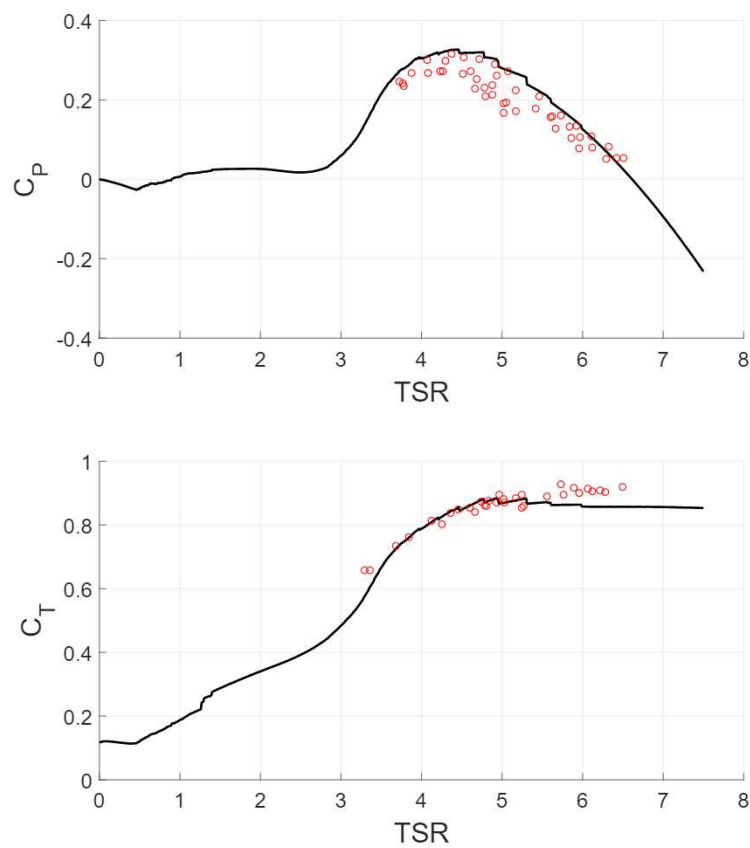


Figure 10: Power and thrust coefficient dependence on TSR. BEMT predictions of load coefficients are shown as black lines, and flume measurements (taken from Stallard *et al.* [31]) are shown as hollow red circles.

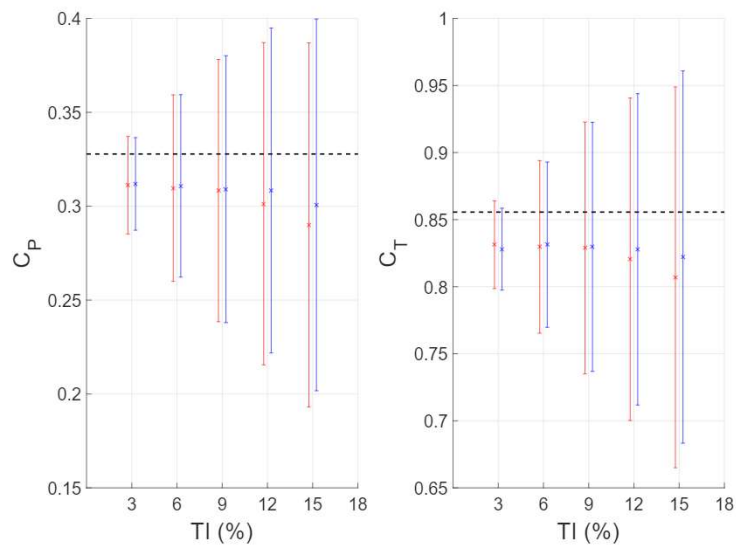


Figure 11: Power and thrust coefficients for simulations of turbine at optimum TSR of 4.4 under a range of turbulent conditions ( $TI = 3, 6, 9, 12, 15\%$ ). Dashed black lines indicate values of power and thrust coefficient in steady flow conditions; crosses and bars indicate coefficient mean values and standard deviations. Results from SEM turbulence are shown in red and those from Sandia turbulence in blue. Note that SEM results are shown with a slight negative offset in TI and Sandia results with a slight positive offset to make it easier to distinguish the results of the different methods, but the actual TI values are as indicated above.

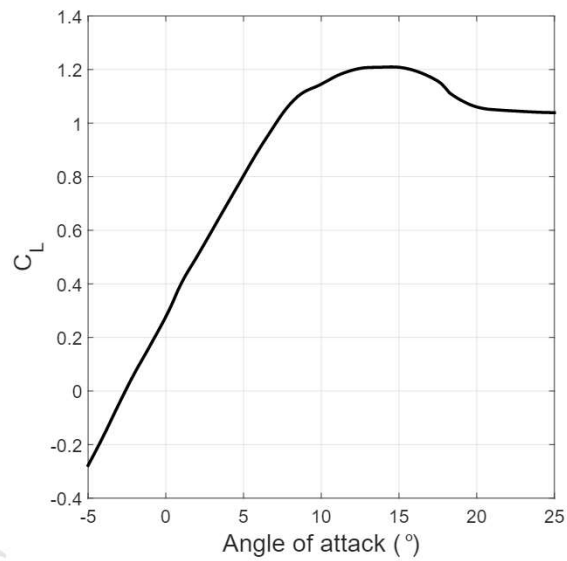


Figure 12: Lift coefficient of the NACA 63418 blade section at  $Re = 6 \times 10^6$ , plotted against angle of attack for a selected range of angle of attack values encompassing stall. Data taken from [26]



ACCEPTED MANUSCRIPT

- We simulate a lab-scale turbine in BEMT in synthetic turbulence flow conditions.
- Two different synthetic turbulence generation methods are compared.
- Rotor thrust and power are less variable in stall than near optimum or overspeed.
- Rotor load variability is seen to be directly proportional to turbulence intensity.
- Turbulent velocity spectra do not necessarily predict load spectra.

ACCEPTED MANUSCRIPT



