Defining a Marine Turbine Condition-Based Maintenance and Management Strategy for Low Velocities in Mexico

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Abstract— **The potential deployment of Tidal Stream Turbines in identified sites around Mexico is considered. An initial assessment of suitable locations is made based upon the nature and level of available resources. The characterisation of these resources is part of ongoing national research activities, summarised herein. One aspect of the specific nature of the available resources can be characterised as low velocity. This will require adaptations to existing turbine designs and to their management and operation. To aid this process the development and potential application of a drive train test rig is presented. Using inputs generated by simulation, laboratory tests and site-specific surveys this rig will be deployed to support the engineering and testing of turbine condition monitoring and management strategies.**

***Keywords*— Condition Monitoring, tidal stream turbine, tidal low velocities, generator test rig, Cozumel Channel.**

I. Introduction

The energy sector is currently dealing with big challenges worldwide: the depletion and scarcity of fossil fuels, a higher energy demand due to population growth, the commitment to protect the environment and equally to mitigate the effects of climate change. There is an emerging market derived from renewable resources to diversify the electric network and hence reduce carbon emissions in the atmosphere. One renewable resource that has attracted considerable attention is marine energy. Within that sector it has been estimated that tidal-stream resources can provide a theoretical energy potential of 3 TW worldwide, exceeding current and future energy needs [1, 2]. Other significant advantages of marine energy are the high predictability, space availability and less competition in offshore resources compared to land-based renewables [3].

Tidal stream turbines (TSTs) present challenges in terms of their operation, maintenance and survivability. In many ways these are similar to faults already experienced by wind turbines, such as corrosion, varying operating speed and load and structural stresses induced by the wind or in this case, marine environment. A potential method to overcome these challenges in the future is to develop a condition-based maintenance strategy. This can be defined as the continuous monitoring of system data to provide an accurate assessment of the health and status of a component or system and performing maintenance based upon its observed health. Such a system may be expected to support TST prognostics in order to estimate the Remaining Useful Life (RUL) of the system and its component elements. This has the potential to increase power availability and reduce maintenance costs and hence to improve the competitiveness of TSTs against other renewable energy technologies [4, 5].

Preliminary economic analysis being developed have suggested that ideally a stream velocity should be between 2 and 3.5 m/s with the resource located within 1 km from the shore and with a water depth between 20 to 40 m [6, 7]. However, in terms of maintenance and system availability, researchers affirm that a lower peak velocity between 1.2 and 1.5 m/s becomes economically viable in locations with continuous or quasi-continuous flows [8-10]. Research is being conducted in Mexico to define the tidal stream energy potential with lower velocities up to 2 m/s in two main sites: The Gulf of California and the Yucatan Channel, at the northwest and southeast part of Mexico respectively, as shown in Fig. 1. The aim of the current research by the authors is to support the deployment of well-designed devices combined with effective management and maintenance to potentially increase operational efficiency and reduce TSTs downtimes. The main justification of this approach is the reduction in costs and/or increased resource availability. These advantages could lead to competitive Levelised Cost of Energy (LCOE), even when deployed in circumstances that would conventionally be viewed as offering lower energy yields.

Research undertaken by the Cardiff Marine Energy Research Group (CMERG) has developed representative TST simulations in a drive train simulator test bed at $1/20^{th}$ scale [11]. This has utilised condition monitoring algorithms to provide non-steady-state verification and monitoring approaches, specifically for rotor imbalance and blade fault simulations. The main advantage of utilising this test rig is to be able to adapt a variety of operating conditions for real time TST simulations, and hence enable the monitoring of turbine performance. As part of a parametric model built for condition monitoring purposes, one of the inputs was used to characterise stochastic on-coming fluid velocities and their fluctuations to represent more realistic conditions [12]. Thus, the aim of this paper will be to determine how a time series fluid velocity simulation will be represented in this research to utilise the Yucatan Channel data, specifically the data recovered from the Cozumel Channel ongoing research, as the first input of the test rig parametric model. Furthermore, the operational parameters to properly extract the marine current energy from the fluid will be presented and discussed. The results that will be presented in this paper will be implemented later in this research to define an optimal solution for low velocities scheme based on condition monitoring performance and cost effectiveness. These will be used to determine an optimal solution for an ocean current application in the Cozumel Channel that provides lower current stream velocities compared to the ones found in the UK.

The structure of this paper will be organised in two main parts: the first will provide an overview of the ongoing resource assessment research in Mexico both happening in the Gulf of California (GoC) and the Cozumel Channel, but will focus primarily on the latter. Then, a methodology definition will be presented in three main stages that should be developed in order to find the optimal solution for low velocities scheme, specifically the ones described throughout this paper.

Fig. 1 Potential sites in Mexico to generate marine energy.

II. Literature Review

A. *Overview of Power Generation in Mexico*

According to the World Bank from 1996 to 2012 Mexico's population access to electricity increased a 3.1%, and by 2012 99.1% already had electricity in their communities and households [13]. Recently, the Mexican government set a policy path to accomplish 35% of electricity generation from clean energy sources by 2024, hence to reduce their dependence on oil and enhance the role of alternative energy sources [14].

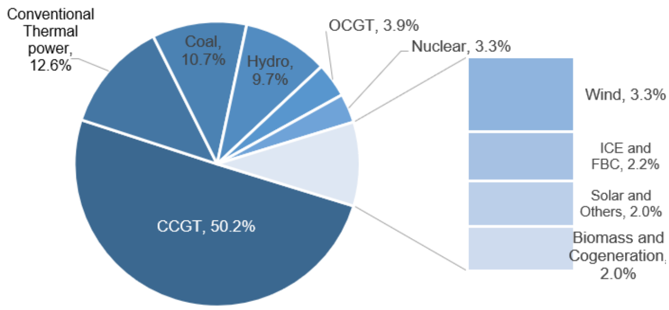

Fig. 2 Gross electric generation per technology type in 2016. (GWh). [15]

It was stated that, in 2016 electric energy consumption was 298,791.7 GWh [14, 15]. Within this the central and northwest part of Mexico represented the highest electrical consumption due to intense economic activity and population density in the central and high temperatures in the northwest. To satisfy this demand, 73,510 MW of installed capacity was used. Overall, 20.3% of the electric generation came from clean technologies, with wind, nuclear and hydro being the biggest contributors. However, 50.2% of the overall production was still satisfied by Combined Cycle Gas Turbine (CCGT) technologies as shown in Fig. 2 [15], which establish a clear outline towards a renewable generation goal.

Forecasts estimate an installed capacity in 2031 of 6.21% and 15.21% of solar and wind energy respectively [15], therefore it can be deduced that the Mexican government is striving to drive renewable energies by these two sources of great energy potential in the country. However, the Mexican government is giving very little consideration for other types of renewables such as marine energy since resource assessment throughout the coastlines is still in progress.

Mexico ranks second in the American continent with the largest ratio of continental coastlines per area [16]. The extension of their 11,122 km of coastlines is divided into two areas: the west (the Pacific Ocean and the GoC) with 7,828 km, and the east (the Gulf of Mexico and the Caribbean Sea which are part of the Atlantic Ocean basin) with 3,294 km [17]. Moreover, preliminary results suggest that in the GoC there is an estimated power of 3.4 GW due to the large tidal range of a mean value of 7 m and a maximum current velocity of 1.5 m/s in places such as Canal del Infiernillo and de Ballenas as shown in Fig. 3, with an overall power output of 5 kW/m^2 [18, 19].

Furthermore, researchers registered velocities in the northern GoC and around islands straits of a mean value of 0.5 m/s based on results taken from July 1997 to March 1998 [20-22]. One of the moorings with a 150 kHz ADCP was placed at 280 m depth measuring currents at nominal depths of 263 m to 33 m every 10 m and it was placed in the northern part of Angel de la Guarda island. It was concluded that the strongest currents (~0.7 m/s) occurred in August and were found in deeper waters. During the winter the drifter velocities reached values of 0.5 m/s, although mean values were in the same order as in the summer season (0.3 m/s). Consideration of water transport across the GoC concluded that the water flow variation throughout the year was minimal [23].

However, research in the GoC is constrained by natural reserved areas of endemic and endangered species and commercial fishing activities [24], thus for the intention of this paper the research will be focused on the Cozumel Channel.

Fig. 3 El Canal del Infiernillo and de Ballenas have the fastest marine currents in the GoC.

B. Cozumel Channel Research

Mexican research in tidal stream energy is focusing on the Cozumel Channel. This is part of the Yucatan Channel, that is the main inflow passage of the Gulf of Mexico (GoM), which is located between the Yucatan Peninsula and the western tip of Cuba and connects the Caribbean Sea to the GoM. From the Yucatan Peninsula to Cozumel island the channel is 400 m depth and 18 km wide. To the east of the island is 1,000 m deep from Cabo San Antonio, Cuba, to Isla Contoy, Mexico [25]. As an attempt to evaluate the theoretical velocity and flow variations of the current between the Caribbean Sea and the GoM, the CANEK program was developed in 1996 [26]. Results were delivered in 2001 by 8 ACDP and 8 mooring array installations across the Yucatan Channel. Hence, relevant information was acquired and processed by different authors [27-29].

The Yucatan Current flows from the south of Cozumel Island and across the western side of Yucatan Channel into the GoM, where it becomes the Loop Current. It portrays a current velocity up to 0.6 m/s, where the velocity is much greater at the surface. Furthermore, the Cuban countercurrent is on the eastern side of the channel where there is an intermittent shallow flow with a velocity of 1.5 m/s near the surface, but it may reach a maximum value of 2.5 m/s in deeper waters. Finally, the Yucatan Channel velocity intensifies when it passes through the Cozumel Channel, where it reaches a mean velocity of 1.1 m/s at 30 m depth [30]. This information has led to an increase on focusing in this area for tidal stream energy extraction, due to its proximity to the shore and its shallow waters.

The current work has been developed by two main research groups in Mexico: CANEK and CEMIE-O. The latter reported numerical models created with data from 1958 to 2012 to represent current spatial patterns of mean and maximum speed values in the surface and in 50 m depth regions [31]. As shown in Fig. 4, the velocities are from 0 to 2 m/s, where the images 3a and 3b show the highest mean values at both shallow and 50 m depth, and images 3c and 3d show the maximum values found again at the surface and at 50 m depth. It can be deduced that the mean values at both shallow and 50 m depth level are practically equal, whilst highest maximum values can be found at surface level (3c) compared to 50 m depth (3d). The highest maximum values are found at the north of the Cozumel Channel, near Puerto Morelos with a mean value of 1.4 m/s and at the East of Cozumel island, with a mean value of 1.2 m/s. On the other hand, current maximum values are significantly higher at the surface (near 2 m/s) compared to 50 m depth which are pretty similar to the mean values found at the same locations (1.6 m/s).

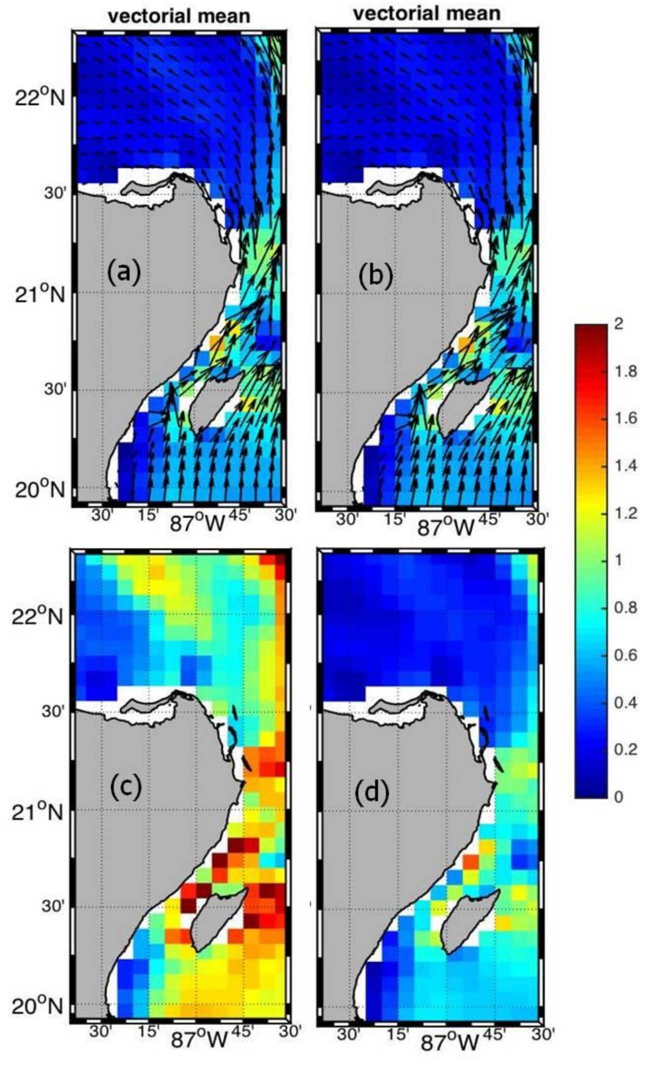

Fig. 4 Mean values from 1958 to 2012 of shallow currents (3a) and at 50 m depth (b). Similarly, maximum values of shallow currents (3c) and 50 m depth (d), both found at the Cozumel Channel. [31]

Similarly, the CANEK research group installed a long-range ADCP of 75 kHz anchorage at 400 m of depth on a specific site as shown in Fig. 5.

During the sampling period the currents were unidirectional northwards with little variation. Mean, maximum and standard deviation values of stream velocities were found between 50 and 100 m as shown in Table I. It was found that the maximum value of 2.3 m/s is at 81 m depth. The most feasible operational velocity option should be used at 49 m, where mean and maximum velocities of 0.97 and 1.84 m/s where found respectively. Future numerical modelling efforts of this project will require numerical models of better spatial resolution (< 1km) and with even shallower waters to become operational feasible (< 30m), plus corroboration of these with measurements aboard boats.

TABLE I: MEAN, MAX AND VSTD VELOCITIES PER DEPTH VALUE

m/s	**Depth (m)**			
	49	**65**	**81**	**97**
Vmean	0.97	1.03	1.05	0.98
Vstd	0.2	0.19	0.19	0.19
Vmax	1.84	1.99	2.3	2.01

Fig. 5 Ongoing research current velocities site from CANEK and CEMIE-O.

III. METHODOLOGY

The process shown in Fig. 6 was chosen to define three main stages of the experimental and testing setup to define the optimum parameters of the TST performance with an upstream low velocity and the procedure that will be followed to simulate real-time drive train behaviour. All these three stages will focus on providing more realistic turbine control process and fluid velocity simulations to develop a condition monitoring and cost effectiveness approach for low velocities. The first two stages will provide the test rig inputs for the third stage, which consequently may provide condition monitoring recommendations and finally the definition of an optimal solution for low velocities. The following sections of each one of the stages on the diagram will determine the concepts that need to be introduced for the further work of this project.

A. *Resource Modelling*

The first input for the simulator test-bed will be the simulation of the tidal stream resource. Previous research has been developed to define how to represent the variation of the current velocity [12, 32]. The flow is represented by:

$$U_x(t) = \overline{U_x} + u'_x(t) \qquad \text{Eq.1}$$

which takes into consideration the average velocity and fluctuations caused by turbulence. Adding turbulence intensity into a time series provides more realistic marine current stream fluctuations than using average velocities. It is worth noting that the fluid velocity at time *t* is considered a stationary fluid process with power spectral density characteristics to represent turbulence. The latter has been characterised previously by its intensity for the $u'_x(t)$ process, which can be defined as:

$$I_U = \frac{\sigma_u}{U} \qquad \text{Eq.2}$$

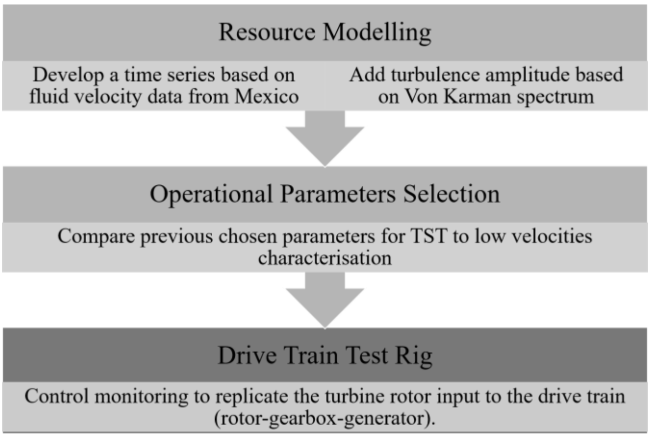

Fig. 6 Process diagram for the definition of optimum parameters for low velocities scheme.

Different turbulence intensities have been defined by researchers, assuming 10 to 13.5% in mean flow velocities greater than 1.5 m/s. However, there are other estimations where there are ~2 m/s flows with the order of 25 to 30% turbulence intensity [33].Therefore, this suggests that turbulence intensity may be site specific and that in Mexico proper data should be taken either from ADCP measurements or estimated values based on comparison of standard deviations from peak spring and neap tides.

As aforementioned, turbulence can be described by its power spectrum $S_u(f)$, where f represents the frequency of fluctuations [32]. Relying on Kolomogrov's theory, turbulence power spectra should become proportional to $f^{-5/3}$ as f increases. Thus, the von Karman spectrum can be written in the non-dimensional form as:

$$\frac{f S_u(f)}{\sigma_u^2} = \frac{\frac{4fL}{U}}{\left[1+70.78\left(\frac{fL}{U}\right)^2\right]^{\frac{5}{6}}} \qquad \text{Eq.3}$$

where L is the integral length scale. Previous research has estimated a value of 0.8 of the channel depth [32]. Thus, if a maximum operational depth chosen in the Cozumel Channel is 49 m based on the above data mentioned in Table I, it can be assumed that the length scale would be $L = 0.8 \times 49 = 39.2$ m. An example of how a MATLAB time series over a tidal cycle will look in the future of this project will be deployed in the next section to demonstrate turbulence intensity and other time-series variations.

B. Operational Parameters Selection

The second input for the test rig will be used to define the optimum parameters of a tidal stream device to be implemented in the low velocities scheme. Limited research has been developed in this area, where different devices have been proposed to increase the mass flow rate over the rotor and speed up the upstream velocity. One theory is to add a duct or diffuser to horizontal-axis tidal turbine (HATT), where the turbine diameter is smaller but an additional area from the duct is added to the device. However, a previous numerical study indicated that ducted turbines have a smaller power coefficient of the total device compared to other turbine sizes [34]. On other work selected commercial ducted turbines have been compared to show that, with a rated flow speed between 2.5 to 3 m/s, an overall device area of 20 m^2 and a rated power of 65 kW, the device can aim to a power coefficient of 0.23 [35]. Considering that current power coefficient values are in the range between 0.40 to 0.45, it appears that ducted turbines have significantly low values in terms of power generation.

Based on the latter, it has been decided that the first TST model to be implemented on this project will be the one previously developed by CMERG [36]. A 10 m diameter HATT with 3 blades model has been represented in a 0.5 m diameter scale device. The blade design is based on an adapted Wortmann FX 63-137 aerofoil profile. The total available power (W) given by the previously mentioned low velocities streams can be represented as:

$$P_O = \frac{1}{2}\rho A U^3 \qquad \text{Eq. 4}$$

where ρ is the density of the seawater (~1025 kg/m^3), A is the rotor swept area and U is the free upstream velocity. Only 16/27 fraction (or 0.59) of the maximum power can be extracted from a HATT, which is known as Betz limit or the maximum efficiency of a turbine [37]. Thus, the power coefficient (C_p) is determined by either the capture area of the device or the flow speed, defined as:

$$C_p = \frac{P}{(1/2)\rho A U^3} \qquad \text{Eq. 5}$$

Furthermore, the thrust coefficient (C_t) is the axial forced applied by the rotor on the current and it is determined by:

$$C_t = \frac{P}{(1/2)\rho A U^2} \qquad \text{Eq. 6}$$

Both previous values are presented as a function of a dimensionless value called tip speed ratio (λ), which is the ratio of the fluid speed to the rotational speed of the turbine blades. Finally, this is represented by:

$$\lambda = \frac{\omega R}{U} \qquad \text{Eq. 7}$$

where R (m) is the radius of the turbine and ω (rad/s) is the rotational speed of the blade tip [38]. Normally, λ and C_p values are plotted against each other to compare turbine performance, looking for the highest C_p possible based on the chosen turbine diameter.

C. Drive Train Test Rig

Inputs into this stage will come from both the fluid time series and the needed parameters for optimum power output extraction based on C_p, C_t and λ values. These will be implemented as part of a parametric model that needs to be defined for this project. The instrumentation deployed to implement this process and obtain TST simulations will be the drive train test rig. Previously, a motor was directly coupled to a generator for power extraction and simulation of a direct-drive TST [11]. However, due to the requirement of increasing the speed to drive a generator which is operating at high speed and low torque and to increase the overall drive train efficiency, it has been decided to add a gearbox between the rotor and the generator. The test rig used to simulate the conditions previously is shown in Fig. 7. It couples two Bosh Rexroth IndraDyn MSK 050Cs (one operating as the rotor and the other one as the generator) via a GTE 120 Bosch Rexroth gearbox. The rotor and generator are synchronous permanent magnet machines rated with a maximum velocity of 4300 RPM and a maximum torque of 15 Nm. The gearbox is a two-stage planetary device with a gear ratio of 20:1. The IndaDrive Cs are connected to a Modbus TCP/IP National Instruments Compact RIO master drive. The latter implements Vector Oriented Control (VOC) to set the torque on each machine and finally obtains an output from each machine in real time. Fig. 7 shows the current coupling between the rotor and the generator, while in Fig. 8 a schematic diagram is used to describe the interaction between the hardware elements.

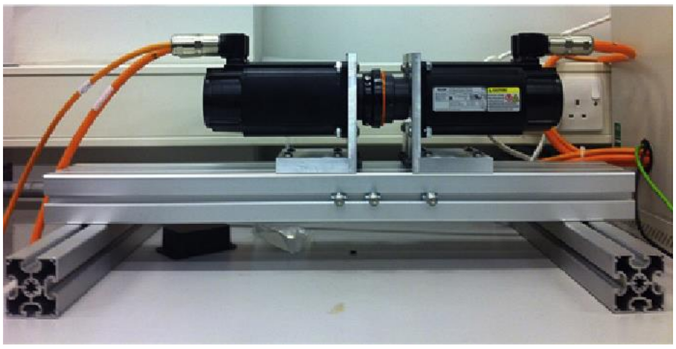

Fig. 7 The drive train test rig utilised previously to replicate direct-drive TST fault conditions.

IV. DISCUSSIONS

Based on the previous methodology, several conditions will have to be met in order to provide an economically-viable solution for low velocities scheme as the ones found in the Cozumel Channel in Mexico. Future research will aim to define the optimal parameters based on real-time simulations on the drive train test rig, and to adapt previous conditions in a holistic study.

The first stage will be to engineer a time series to add turbulence intensity. This will be achieved either by creating a synthetic signal using the concepts of fluid time series and Von Karman spectrum as detailed above, or by obtaining real results from ADCP measurements. In previous research a developed fluid time series was compared with flume tank data utilising CMERG 0.5 m diameter turbine [11]. Subsequently, it was further manipulated to simulate fault conditions and turbulence intensity to provide simulated data that was used as the test rig input. The further research in consideration will adapt real-time ADCP measurements to the fluid time series while comparing this data with further flume tank experimental analysis. Fig. 9 displays an adaptation example of aforementioned values in a time series, adding noise amplitude into the signal.

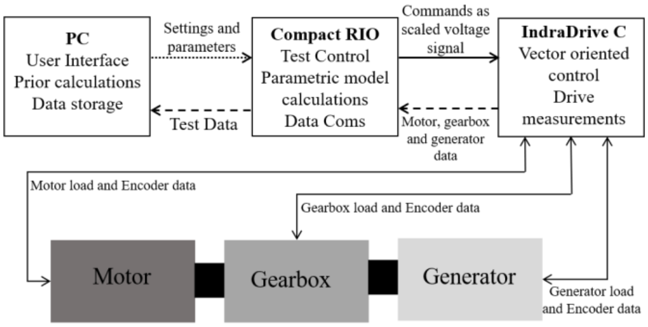

Fig. 8 Indirect-drive Train Test Rig Diagram and the distribution of functionalities across the hardware platforms.

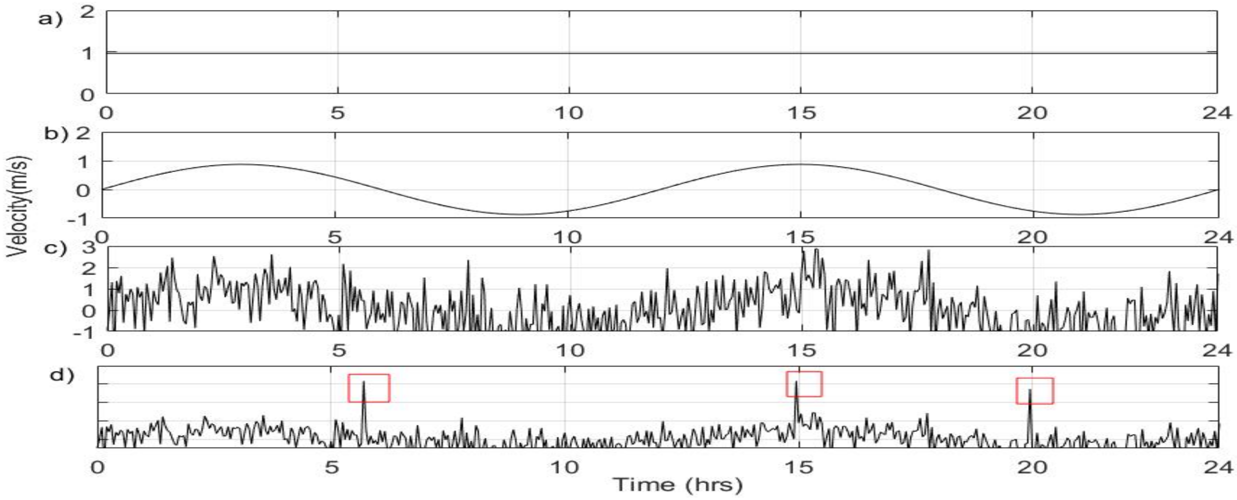

Fig. 9a) Constant mean value of 0.97 m/s found in a 49 m depth. 9b) Marine current velocity with a maximum value of 1.84 m/s and a STD of 0.2 in a 24 h interval. 9c) Noise added to the previous sinusoidal signal. 9d) Fluctuations simulation that may interfere with a time series input to the test rig.

First, a constant value of a stream velocity of 0.97 m/s in 49 m depth is assumed in a day cycle (9a). Then, given a maximum value and a standard deviation of 1.84 m/s and 0.2 respectively, a sinusoidal signal is represented with two ebb and flood tides within a 24 h interval (9b). Furthermore, a representative noise signal has been added to the previous sine wave, which in further research will replicate turbulence intensity and other variation conditions in the constant values (9c). Finally, a characterisation of fault conditions and causes of turbulence variations (i.e. stanchion shadowing effect, offset blade and rotor imbalance) in a 24 h interval is presented in (9d). These conditions will be developed and properly analysed in the future to determine possible fault conditions that might interfere with the first test rig input.

The second input to the test rig will be to determine the optimum parameters of C_p, C_t, λ and turbine diameter values. The typical C_p and λ graph comparison produced by CMERG may be used as reference in order to demonstrate the importance of validating a break-even point for the latter values to considerate low velocities [39].

In Fig. 10 an example of a C_p vs TSR for different inlet velocities from 1 to 3.08 m/s and turbine size from 10 to 30 m is shown. Overall from this study, it can be said that C_p and λ are not affected by the turbine diameter or upstream water velocity providing Reynolds independence has been reached. Either changing the turbine diameter or the upstream water velocity, C_p collapses into a single curve. Given that these were simulated under a plug flow velocity of 3.086 m/s and a turbulence intensity of 5% as the ones found in the Severn Estuary in the UK, similar results would have to be performed to characterise the optimal TST turbine to be utilised by lower velocities.

Using these terms, it should be possible to analyse whether a larger or smaller rotor diameter should be developed. Work may also consider the possibility of reducing losses by increasing the rotational speed of the blade tip in order to be able to extract the highest potential energy output from low velocity marine currents. Furthermore, another way of reducing C_p losses is by reducing turbulence intensity, which the Cozumel Channel could potentially reduce this effect due to its steady and little variability flow conditions. Therefore, one can deduce that Mexican marine currents has a slight advantage compared to the ones found in the UK due to the little fluctuations currently found in the Cozumel Channel that could potentially increase overall power generation, albeit the fact that the current velocity itself could be potentially slower. To support this consideration further measurements will be performed to characterise the Cozumel Channel in order to find the most optimal location to exploit this energy.

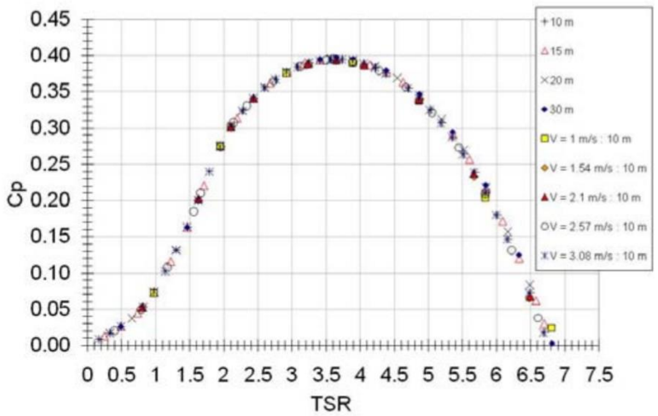

Fig. 10 An example of C_p compared to TSR with increasing turbine diameter (10 to 30 m) and upstream water velocity (1 to 3.08 m/s) [39].

Finally, another term to be analysed will be the need to increase the energy yield throughout the direct-drive TST drivetrain. As previously mentioned, this will be simulated in a drive-train test rig previously utilised by CMERG. The further improvements to the test rig will be to add new drivers and increase the capability of real-time simulations, to add a gearbox to reduce the torque to drive the generator and finally to use low velocities scheme to determine the economic-feasibility of these conditions. On the other hand, a parametric model will need to be defined to utilise the previous C_p, C_t and λ data to characterise the simulation of real-time TST.

It is claimed that the gearbox might increase the motor efficiency at faster rotational velocities, however it may also have some small losses such as noise, heat and strain. Adding a gearbox onto the test rig will allow to simulate an indirect-drive TST which is a prominent design in the current generation of TSTs. On the other hand, it has been considered to offer simulations flexibility by removing the gearbox and going back to direct-drive, to understand the generator performance when operating under both direct-drive and indirect-drive turbine operation to ultimately define turbine management and monitoring.

In addition, future research will need to define a proper scale for flow conditions in the test rig due to Reynolds number dependence [40]. If the challenges mentioned above are overcome throughout this research, then it will make a significant contribution to an optimal solution that could be deployed to extract the marine energy potential found in Mexico. This will need to satisfy the social and economic national needs and to define a management strategy to reduce operational costs. Hence, by defining the latter, a comparison between faster and lower velocities could be performed to define the best economic-viability in operational terms.

V. Conclusions

A methodology definition to approach a low velocities scheme as the ones found in the Cozumel Channel in Mexico has been described. A literature review of the previous research performed in Mexico has been used to support the goal of establishing the likely possibility of extracting marine energy from the flow stream currents presented in the Cozumel Channel. A three step methodology keys has been defined in order to further analyse the variables and their composition. These will be utilised in a drivetrain simulator test bed that has already been developed by CMERG. Finally, it has been established that low velocities scheme could potentially reduce operational costs due to less turbulence intensity and TST downtimes, but further research needs to be developed in order to approve such theory.

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