Multi-model analysis of tidal turbine reliability

Michael Togneri, Elaine Buck, Alasdair MacLeod, Erwann Nicolas, José Nuño, Michael O'Connor, André Pacheco, Grégory Pinon and Ian Masters

Abstract—**We present a description of a method for analysing the reliability of tidal energy converter (TEC) blades and structures using a range of models. The investigation is motivated by the observation that the most important barrier to growth of tidal stream energy as a significant contributor to low-carbon electricity generation is its cost, and the largest technical factor contributing to cost is the expense of planned and unplanned maintenance. The analysis employs five main models, looking at: variability, measurements of full-scale TEC prototypes, laboratory experiments, numerical simulation and technoeconomics. The paper gives a brief summary of the problem which this analysis is meant to address and the context in which it is applicable, and describes the project designed to support the development of the analysis method. We then briefly introduce the modelling approaches used in the project, giving both a broad context for each field and details of the specific techniques employed in the current work. Following this introduction, the work that has already been carried out is summarised, and the plan for the remainder of the project lifetime is presented.**

Keywords—**Tidal energy, reliability, VMEA, at-sea testing, laboratory testing, BEMT, VPM, technoeconomics.**

I. Introduction

RECENT analysis has shown that the single biggest factor contributing to the overall levelized cost of energy (LCOE) for tidal stream applications is the expense of operations and maintenance (O&M) [1,2]. This is not unexpected for a sector that has not yet benefitted from the improvements that become apparent from long-term deployments: existing renewable energy technologies have seen costs decrease at rates around 20% as the deployed capacity increases [3], and a recent report prepared for the UK's Department of Energy and Climate Change suggests that operating expenses for tidal stream energy devices could see a rate of decrease of around 19% as more capacity is brought online [4]. A particular cost driver for the tidal energy industry, however, is the expense of operations at sea [5]. It is far more costly to deploy a lift-capable vessel to retrieve a tidal energy converter (TEC), bring it back to dock for maintenance or repairs, and then redeploy – particularly taking into account the tight operational windows necessitated by the strong currents at suitable tidal energy sites – than it is to carry out similar operations for devices that are more accessible for in situ repairs. There are two halves to this expense: firstly, how much a given operation costs; and secondly, how often it is necessary to carry out operations. Reductions in the cost of individual operations is expected to follow the 'learning by doing' that will inevitably accompany the deployment of more tidal stream energy capacity [6]; to reduce the number of operations, we must look to improve TEC reliability.

This paper describes the methods of the MONITOR project - a collaborative "multi-model" investigation of TEC blade and structure reliability, which brings together multiple testing methodologies (numerical, laboratory and at-sea) and links their findings through a central reliability model. This central model is variation mode and effect analysis (VMEA), a systematic means of identifying and quantifying the factors contributing to variability of a key parameter or parameters [7]. In the current study, the "key parameter" is the blade lifespan – by using VMEA to more accurately identify the sources of variation that impact blade life and thus quantifying technical risk, this investigation will enable more robust TEC designs with less conservative engineering safety factors.

This quantification of risk requires knowledge of both the flow conditions that a TEC will experience, and of the structural loads that certain flow conditions will result in. The ideal for this is simultaneous measurement of flow conditions and loads on a real turbine, but neither flow nor load measurements are straightforward to measure. Flow conditions are most commonly measured with acoustic Doppler current profilers (ADCPs), which are very powerful tools but fundamentally rely on several

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E. Buck is with the European Marine Energy Centre, Old Academy, Stromness, Orkney KW16 3AW, UK.

A. MacLeod is with the Offshore Renewable Energy Catapult, Inovo, 121 George St, Glasgow G1 1RD, UK.

E. Nicolas is with Sabella S.A.S., 11 Rue Félix Le Dantec, 29000 Quimper, France.

J. Nuño is with Magallanes Renovables S.L., Prego de Montaos 7, Redondela, Spain, 36800.

M. O'Connor is with University College Cork, College Road, Cork, Ireland, T12 YN60.

A. Pacheco is with CIMA, University of Algarve Edificio 7, Campus de Gambelas, 8005-139 Faro, Portugal.

G. Pinon is with LOMC, University of Normandy-Le Havre, 25 Rue Philippe Lebon, 76000 Le Havre, France.

I. Masters and M. Togneri (corresponding author) are with MERG, College of Engineering, Swansea University Bay Campus, Swansea SA1 8EN, UK (M.Togneri@swansea.ac.uk).

simplifying assumptions about flow at the measurement sites [8]. Instrumentation for loads on full-scale devices at real sites is more straightforward to obtain, but no full-scale device has been installed for pure research purposes – thus, no such load data is publicly available for reasons of commercial sensitivity. Although at-sea testing is of course the 'gold standard' for investigation of TEC behaviour, there is the drawback that it is not possible to control sea conditions.

To supplement data from real, full-scale turbines, laboratory testing offers greater (but not unlimited) control over flow conditions, with the tradeoff of introducing scaling and boundary effects [9]. Nonetheless, laboratory testing is one of the most valuable techniques available for understanding the link between flow conditions and load variability [10], and thus a crucial tool for providing quantitative data to the VMEA model of TEC reliability.

Numerical modelling offers a still greater degree of control over flow conditions, enabling investigation of extreme events (e.g., 100-year waves) or fine-grained distinctions in turbulence [11] that are not possible even with lab testing. However, care must be taken in validating models against empirical data, otherwise we can have no confidence in the numerical data for test cases that cannot be physically realised.

As a barrier to industrial development, reliability is not a purely technical problem but also an economic one. The investigation described in this paper therefore also considers how the findings from the at-sea, laboratory and numerical modelling impact not just the reliability of the devices but also, ultimately, the cost of developing and operating them. A well-established model from wave energy devices is adapted for use in a tidal stream application [12].

The multi-model investigation of TEC reliability described here has been running since early 2018, and is foreseen to conclude by 2021. The aim of the MONITOR project is to produce a VMEA model of tidal turbine blades and structures that is easily generalisable to any conventional horizontal-axis design; this is achieved by first carrying out a pair of case studies, and then extrapolating a general model from these specific instances. In this paper, we first present a brief introduction to the methods used in the investigation, then a discussion of what has been achieved so far and our expectations for how it will proceed in the coming years.

II. Methods

A. VMEA

The VMEA is a method that allows engineers to systematically identify the factors leading to variation in key performance characteristics (KPCs) of a device or a component [7,13]. A suitable KPC for the investigation of TEC reliability would be, for instance, expected blade life – this is the KPC chosen for the VMEA modelling in the current project. Once the KPC of interest for a particular analysis is identified, the engineer carrying out the analysis will identify factors that influence the KPC (e.g., for blade life we would look at environmental loads, blade material properties etc.) – these are the so-called sub-KPCs. The factors that affect the variability of the sub-KPCs,

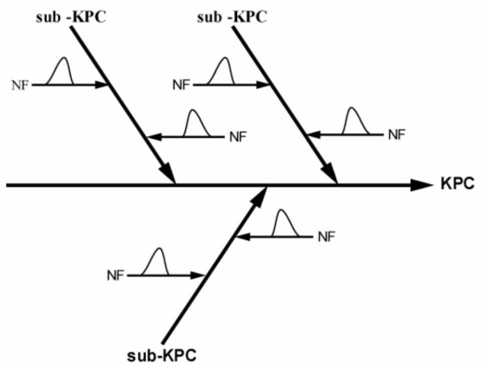

Fig. 1. Relationship between KPC, sub-KPCs and NFs [7].

referred to as noise factors (NFs) are in turn identified. This relationship is visualised in figure 1.

VMEA is most useful when we do not have *a priori* full knowledge of the relationship between the NFs and the KPC – where it is possible to state this relationship with an analytical function, VMEA becomes identical to the method of moments for propagating variability [14]. Such perfect knowledge is very rarely possible in practice and it is necessary to employ engineering judgement – VMEA is a robust method for systematising this approach.

Once the identification process is complete, a preliminary or basic VMEA model of the component is completed by estimating first the variability of the NFs, and then the degree to which these influence the sub-KPCs and, in turn, the KPC itself i.e., the degree to which the NF variability is transmitted into the KPC. To improve this estimate, additional data needs to be collected – a VMEA model that is refined by additional data collection is called enhanced or probabilistic [15].

For the MONITOR project, we achieve this refinement through three test methodologies. As an example of the NF to KPC causal chain, environmental factors such as wave climate or marine current turbulence are key NFs – their variability can be determined through measurements of real sea conditions. In turn, measurements on full-scale turbines can allow us to accurately determine the sensitivity of blade loads (a sub-KPC) to this NF in the conditions encountered in the at-sea testing. The full-scale measurements also yield a means of validating laboratory tests and numerical simulations (taking account of scaling effects, cf. section III-C), which can provide data on the NF to sub-KPC to KPC links for flow conditions that were not encountered in at-sea tests but are nonetheless needed for a complete model of the causal relationship between environment and loads. This combination of modelling approaches is what will allow the MONITOR project to determine the dependence of blade life variability on environmental factors.

B. *At-sea testing*

Data from at-sea measurements at tidal stream sites and on tidal turbines can by and large be assigned into two categories: measurements of the environmental conditions (e.g., resource assessment, wave and turbulence estimation) and measurements of turbine loads and performance (e.g., power produced, floating platform motion). Measurements of both types are key for a reliability model, but far more is available in the way of environmental data than device-specific data. This is not surprising, as all full device deployments and most scale model deployments are commercially sensitive and therefore not made publicly available.

Many estimates of tidal resource are made with numerical models, as single-site measurements obviously cannot provide sufficient information for a selecting a deployment site. Nonetheless, field measurements of resource have been reported for a range of sites, including some of the most important tidal energy locations globally [16,17,18]. As well as considering the resource, measurements at sea have examined other significant environmental factors such as turbulence [19,20].

Despite the commercial sensitivity of load and performance data, a few studies have published measurements from real deployments of scale models or even full-scale devices. One of the most important early TECs was the two-bladed SeaGen device in Strangford Lough; this was the first full-scale device that generated electricity to a national grid. Its deployment was preceded by a scale model (“Seaflow”) off the coast of Devon, and a detailed report on the testing of the Seaflow device is available that briefly describes the power output [21]; there were, however, no instruments installed on Seaflow that would have been able to measure blade or support structure loading. Around the same time, a direct-drive three-bladed device was tested by towing from a vessel; this study again produced power performance characteristics but not loading data [22].

The use of a moving vessel to test TECs is particularly suitable for devices that are mounted on floating hulls. This may be done with a purpose-built vessel such as the tests carried out with the TTT platform in Strangford Lough [23,24], or by a tugboat or similar vessel used to tow the hull on which the turbine will be finally deployed [25].

One of the turbines tested on the TTT platform was originally intended for use as a commercial demonstration prototype, the 1kW Evopod 1:10 scale device (hereafter the E35). Following a change in developer strategy, the E1 passed into the ownership of the marine energy research group at the University of Algarve, who carried out an extensive study of its performance and loads [26] in a tidal energy sites that is already well-studied [27]. This measurement campaign yielded an extensive dataset covering a wide range of environmental and device parameters, including power output and mooring line loads; this real data was used to refine and validate a simulated array deployment in the same environment [28].

Another very valuable dataset of real turbine measurements was obtained through an extensive collaboration between developers and researchers on the ReDAPT project, which ran between 2013 and 2015 and gathered extensive flow, performance and load data on a full-scale 1MW tidal turbine [29]. Much of the flow and other environmental data is publicly available through an online database, although the bulk of the load and performance data remains confidential. Nonetheless, the studies carried out with this data shows how invaluable real measurements are for validating the ability of numerical models to predict performance [30] and load [31,32] of full-scale TECs.

C. *Laboratory testing*

Taking measurements from full-scale turbines at sea is the highest-possible fidelity approach to data gathering for TECs. However, the difficulties outlined above (commercial sensitivity, practical challenges, lack of control of flow conditions) mean that we cannot rely solely, or even chiefly, on data from this source. The current field of TEC research has also relied heavily on laboratory experiments to measure performance and loads on turbines, using equipment such as tow tanks and cavitation tanks [33], or closed-circulation flumes [34].

Lab conditions allow a much more flexible and accessible suite of instrumentation, with a far greater capacity to check that instruments are working as intended (leading to overall greater reliability of data acquisition) and at least some ability to change instrumentation setup on-the-fly. In addition, labs allow measurement of parameters that are simply not practical to examine in the field, such as wake interactions between turbines [35] or permeable discs that replicate turbine thrust properties [36], and array layouts [37] – clearly it is not practical to modify the spatial configuration of a full-scale multi-turbine array in real seas after deployment for an experimental study.

The research community has gradually established widely-accepted standards and conventions for laboratory studies of TECs, and a landmark study showed the extent to which it is possible to compare measurements from different experimental facilities [9]. The steadily-growing interest in TEC research (and related topics such as wave energy, floating offshore wind etc.) has led to the creation of dedicated test facilities which can control test conditions to a far greater extent than was previously possible [38,39].

For MONITOR, the laboratory test portion of the overall project was carried out in the IFREMER combined current and wave recirculating flume [40], which allows a fine degree of control over both turbulence and wave conditions, the key environmental factors impacting TEC load variability. Previous studies carried out in this flume have closely examined turbulence effects on single turbines [41] and small arrays [42], but subsequent technical refinements now allow finer control over turbulence level.

D. *Numerical modelling*

Compared to laboratory tests, numerical modelling offers a still greater degree of control over flow conditions, turbine geometry, control schemes etc. In addition, computational simulations make a much richer data set available as there is no need to consider instrumentation, and also make it much easier to test several similar cases that might be impractical with physical models: for instance, it is far easier to slightly adjust a TEC's blade thickness and remesh a CFD model than it is to manufacture multiple blades, especially if this adjustment is to be made 'on the fly'. The principal limitation, of course, is that the modeller must be able to provide assurances that their model accurately reflects the true problem.

For TEC related problems, numerical modelling can consider a range of spatial scales, from ocean- or basin-scale predictions of resource [43] to large arrays [44] to single TECs. The individual TEC scale is the one most relevant to the MONITOR project, and our investigation will make use of two independent models in order to validate our results: blade element momentum theory (BEMT) and the vortex particle method (VPM)

BEMT has been used as a tool from the very earliest studies on TEC design [45], and is widely used in industry. Its basic premise is that a turbine can be treated both as a momentum sink/source for the fluid flow, and also as a collection of two-dimensional hydrofoils – since these two analyses must be in agreement, equating them allows us to find a unique solution for the loads (and therefore also the performance) of the TEC. It is a very quick solution method, but requires a number of semi-empirical corrections to deal with phenomena such as non-2D flow around the tips of the blades, and additionally it cannot be extended to simulate interaction of multiple devices. The specific BEMT code used in the MONITOR project is a robust solver developed at Swansea university [46,47] that has been used for both academic research and industrial applications.

The VPM method used in the MONITOR project is somewhat more computationally intensive than BEMT, but offers a significantly more detailed picture of force distribution around the blades [48]. This model has been well-validated against experiment [49]. In addition to greater detail in force distributions, VPM also offers an advantage over BEMT in that there is a clear path to extending the model to installations of multiple devices, which is a key opportunity for future development of the results of the MONITOR project.

E. *Technoeconomic modelling*

From a market point of view, device reliability is only interesting insofar as it impacts the final cost of energy, however that is measured. A well-established model that has been used for assessing the economic feasibility of wave energy device deployments is being adapted for tidal applications [12]. This method accounts for a wide range of input parameters (e.g. costs of device fabrication, cable installation etc.) and looks at how sensitive the economic viability of the overall installation is to each of these factors, as measured by the net present value or internal rate of return of the project. A quantified improvement in reliability will most directly impact the costs associated with operation and maintenance, as well as the power generation associated with increased device availability – a device that requires less unplanned maintenance will be generating power, and hence revenue, for a greater proportion of the time. There are also additional indirect factors through which improved reliability may affect costs e.g., by increasing the time interval for planned maintenance, by decreasing insurance costs and by potential reductions in the cost of manufacturing (increased confidence in variable loads allows lower safety factors at device design stage).

The uncertainty in costing marine renewable energy devices is a significant barrier to developers seeking funding, and equally to investors seeking assurances [50]. The MONITOR project's combination of multiple testing methodologies will aid the technoeconomic tool to make predictions of tidal energy costs with a higher degree of certainty than has heretofore been possible.

III. Preliminary Results

F. *At-sea testing*

The MONITOR project aims to develop its general TEC reliability model in the first instance by attempting to implement the methodology for real-world turbines: the floating ATIR turbine developed by Magallanes Renovables S.L., and the bed-mounted D10 and D12 turbines developed by Sabella S.A.S. These devices are depicted in figures 2 – 4.

The ATIR device operates two three-bladed coaxial horizontal-axis turbines on a single floating platform resembling a hull. The two rotors are identical, with a diameter of 19m and a maximum power output of 2MW. The hull on which the nacelle is mounted is 45m long and 6m wide, and the device is anchored to the seabed by stern and bow mooring lines. The full-scale prototype of this device has undergone tow tests in the Vigo Estuary, and

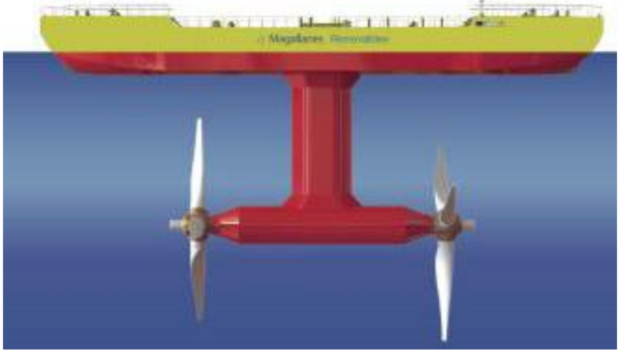

Fig. 2. Schematic side view of the Magallanes ATIR rotor.

Fig. 3. Image of the Sabella D10 rotor on dockside.

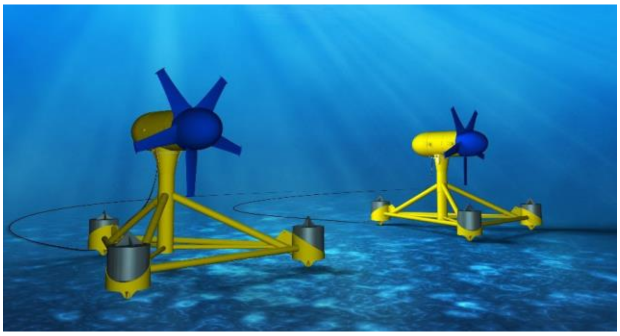

Fig. 4. Proposed design of the Sabella D12 rotor in small array configuration.

was installed at EMEC in Orkney for fixed-location tests in February 2019.

The D10 and D12 devices are bed-mounted horizontal-axis turbines, of 10m and 12m diameter respectively. Both devices are designed to operated in rectilinear flows, which means there is no yaw capacity and the rotor can be driven by flows from either direction. This also means that the blades are designed with a symmetrical section. The D10 has already completed a year's deployment in the Fromveur Strait, near Ushant in France, between summer 2015 and summer 2016; it was redeployed in October 2018 for a second year-long testing period; the D12 is still at the lab-scale testing stage.

As mentioned at the start of this section, the ATIR and D10 devices are currently deployed at two different locations, and it is these deployments that MONITOR will make use of in order to obtain at-sea measurements to refine the VMEA model. Both deployments will measure environmental factors, loads and performance data. Due to differences in the designs and deployment locations of the two devices, it is not possible for the instrumentation to be identical for the different cases; however, one of the key aims of the measurements campaigns carried out as part of MONITOR is to ensure that the data obtained from the two device deployments is in some sense equivalent, and therefore possible to meaningfully compare. The benefit of these measurements is twofold:

1) The data itself can be used to more accurately quantify both the load variation itself and the sensitivity of that variation to the measured environmental factors.
2) The data will also allow validation of the numerical models of the turbines; these validated models can then be used to investigate environmental conditions that were not encountered in the tests, or to simulate the turbine response to different deployment locations.

The measurement campaigns for both devices will take place in summer and spring of 2019.

G. *Laboratory testing*

As discussed in section II, the lab tests under the aegis of MONITOR are carried out in the IFREMER flume tank in Boulogne-sur-Mer. Both of the test campaigns planned for MONITOR have already been completed, in May and November of 2018. Analysis of the data is ongoing, but some preliminary results are already available. A paper presenting these results in more detail is also being presented at this conference [51], but we briefly summarise the tests and present some key results here.

The flume tank used for the tests has a working section 18 m long, 4 m wide and 2 m in depth. A vertical support on which a turbine is mounted can be lowered into the tank from above; the nacelle and internal workings of the turbine remains the same for testing different devices, but different blades can be mounted on the turbine to represent different devices. In addition, external fairing can be added to the basic nacelle to represent different support geometries. For the scaled rotors used in the test, the blockage ratio in the working section varied between 3.5% and 5.1%. The lab-scale rotors matched the full-scale rotors in Froude number, but matching Reynolds number is not practically achievable; however, the results obtained indicate that at the highest flume velocities, the results are no longer highly sensitive to the Reynolds number.

During the flume investigations, the Magallanes Renovables ATIR and Sabella D12 rotors, as well as an open-geometry 'generic' rotor previously tested at IFREMER, were operated in a range of flow conditions. The mean flow U_∞ was in the range 0.8-1.4 ms^{-1} (corresponding to velocities between 3.6-7.4 ms^{-1} for the full-scale turbines) , turbulence was set to low (turbulence intensity, I_∞, of 1.3%) or high (I_∞ of 15%), and a variety of wave conditions with periods between 1.43-2 s and amplitudes between 0.095-0.130 m were imposed – this is the equivalent of wave heights between 3.8-7.3 m and a wave period ranging from 6.4-10.6 s at full scale.To measure the flow conditions, the flume is equipped with 2D LDV and an ADV, as well as three wave probes at the surface. In addition to this, the turbines are fitted with torque and thrust probes. The thrust cell is mounted on the rotor shaft itself, so it is able to directly measure the hydrodynamic thrust and is not biased by the drag on the nacelle and support structure.

Some key results of this investigation are shown in figures 5 & 6: specifically, these figures show the mean and standard deviation of the power coefficient C_P for the three scaled turbines at a range of mean flow speeds and two

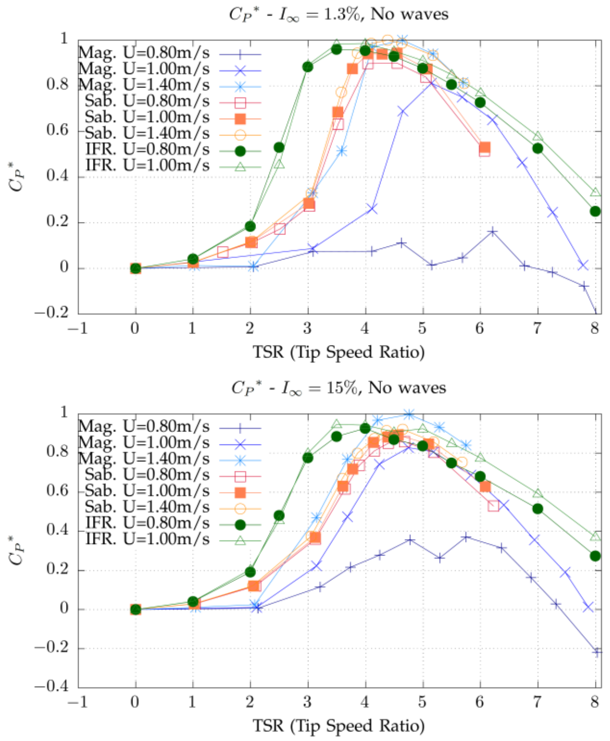

Fig. 5. Anonymised mean C_P results in low-turbulence (top panel) and high-turbulence (bottom panel) conditions for Magallanes, Sabella and IFREMER turbines at a range of mean flow speeds.

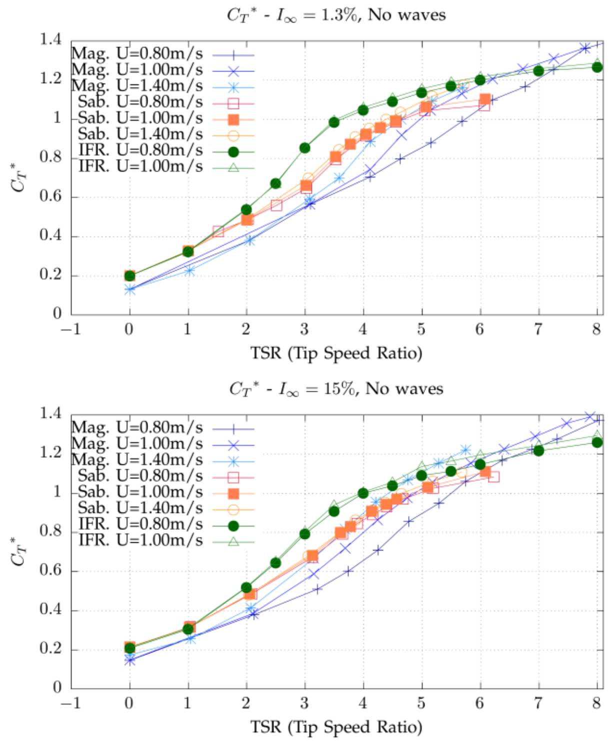

Fig. 6. Anonymised C_P standard deviation results in low-turbulence (top panel) and high-turbulence (bottom panel) conditions for Magallanes, Sabella and IFREMER turbines at a range of mean flow speeds.

different turbulence levels (waves are not considered in the results shown here). An important thing to bear in mind with these figures is that the Magallanes results do not reach Reynolds independence, or at least approximate independence, until the mean flow is 1.4 ms^{-1}, so only those results should be examined. Additionally, for reasons of commercial sensitivity, all C_P and σ_{CP} data for any given rotor has been anonymised by scaling with the maximum value of C_P in the low turbulence case – the resulting value is denoted C_P* and, as would be expected from the scaling, is exactly 1 in the top panel of figure 5.

The D10 and ATIR rotors show remarkably similar performance characteristics in the anonymised data. Both reach optimum performance at TSR values between 4-5, and have similar drop-offs in both stall and overspeed. The variability of the devices' performance, as seen in figure 6, also appears to be extremely similar, particularly around optimum power production. However, the scale of the load variability is greatly affected by the ambient turbulence (compare the vertical scales of the two panels in figure 6) – this implies that load variability may be dominated by environmental factors, and that device design choices can do little to mitigate it.

Although both flume measurement campaigns are now complete, there was a wealth of data gathered and analysis is ongoing. A more detailed discussion of findings from the analysis already performed is presented in [51], but there will be additional analysis shown throughout the lifetime of the MONITOR project.

H. Numerical modelling

Preliminary BEMT simulations of the D12 and the ATIR rotors in uniform flow have been carried out to obtain a numerical baseline for the performances of these two devices. The power and thrust performance according to these simulations is visualised in figures 7 and 8. As is the case with the experimental data, these results have been anonymised: C_P is scaled by its maximum value, and C_T is scaled by the value of C_T at the optimum TSR (i.e., the same TSR at which C_P reaches a maximum).

These results diverge somewhat from the experimental results shown in figures 5 & 6. In particular, we see that the power optimum for the ATIR rotor is predicted to occur at a slightly higher TSR of roughly 5-6, and that the power fall-off in the overspeed region at TSR values beyond this is much more gradual than observed experimentally. In certain regards, the stall behaviour is closer to what is seen in the experimental results. For the ATIR rotor, in stall (i.e., low TSR values) the power output drops from optimum to roughly zero at a TSR of approximately 2 in both experiment and numerical investigation; for the D12, the stall is more gradual; this matches what is seen experimentally.

The most plausible explanation for the more gradual power decrease in overspeed seen with numerical predictions compared to experimental results is tied to a simplification of the ATIR geometry in the BEMT model. In reality, the ATIR rotor blade is based on a single family of hydrofoils that varies in thickness, becoming very thin at the tip and widening out to fully cylindrical at the root

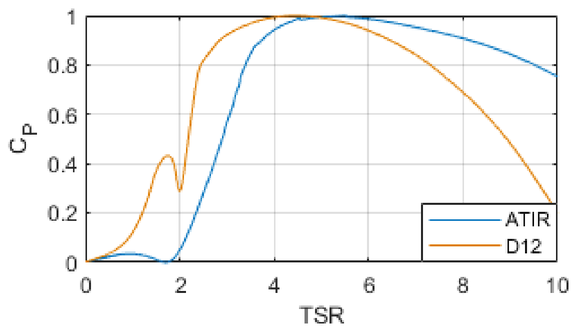

Fig. 7. Anonymised C_P-TSR results in uniform flow for ATIR and D12 rotors calculated using the SwanBEMT code.

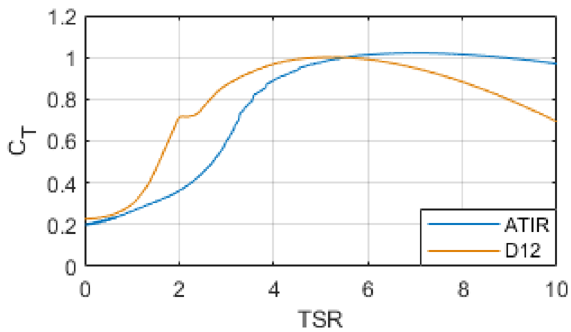

Fig. 8. Anonymised C_T-TSR results in uniform flow for ATIR and D12 rotors calculated using the SwanBEMT code.

for structural reasons. The lift-drag properties of the rotor therefore vary radially. However, in the BEMT formulation, all radial locations are treated as having the same lift-drag curves – we select the properties at approximately two-thirds radius to apply to the whole rotor, as this is the radial location that contributes most significantly to torque in optimum operation. Thicker sections tend to have a lower lift-drag ratio, and so applying these properties over the full radial extent of the blade means that the near-root sections are predicted by BEMT to have better performance than they will have in reality. As TSR increases, the radial span of the blade with the greatest influence on power production moves gradually inwards: thus, in this case, we would expect that the BEMT model will predict higher power performance at overspeed TSR compared to empirical observations, and this is exactly what we see comparing figure 7 with figure 5.

One feature present in the numerical prediction of the D12 results that is not seen in the experiments is the narrow peak in anonymised C_P that occurs around TSR 1.5; this is associated with the post-stall lift recovery of the hydrofoil section. It is possible that this spike is present in the experiments but simply not detected, as the experimental procedure focussed on TSR operation near optimum, with relatively few tests at very high and very low TSR. Thus, the narrow peak may have been missed between the experimental tests at TSR values of 1 and 2. It is also quite plausible that this peak may be a purely numerical artefact, as dynamic stall is not modelled in the BEMT code but is likely to play a significant role for the experiment.

I. VMEA

Preliminary VMEA analyses have been carried out for both the ATIR and D12 devices, although at this stage the data from the laboratory experiments and numerical simulations described above has not yet been incorporated. It is not possible to give a detailed discussion of these preliminary reports due to their commercially sensitive nature, but we present some broad outlines of the conclusions here.

Unsurprisingly, as the different support structures of the floating and bed-mounted devices put the rotors at different locations within the water column, variation due to environmental factors differs from one device to the other. Load variation on the floating ATIR device is more strongly affected by wind and wave than by turbulence in the tidal currents, while for the fully-submerged D12, load variation is almost completely unaffected by wind, but both wave and turbulence action is significant. Design and operational parameters are not discussed here, but these also depend on the details of the devices and their operational strategies, and therefore differ from one device to the other.

J. Technoeconomic modelling

The technoeconomic modelling aspect of MONITOR is highly dependent on the outcomes of the enhanced or probabilistic VMEA model; we do not foresee significant work of this portion of the project to take place until the other models are further advanced. Preliminary work has been undertaken to ensure that the existing model for wave energy converters and arrays is easily adaptable to TECs.

IV. Conclusions

Tidal stream energy has the potential to be a significant contributor to decarbonisation of the energy sector, particularly within Europe. Ocean Energy Europe have estimated that there could be up to 1.8GW of ocean energy capacity installed in Europe's coastal waters by 2030 [52], and up to 100GW by 2050; DG-MARE predicts up to 20,000 European jobs in the sector by 2035 [53]. However, to achieve this it is necessary to overcome the obstacle of energy cost, and the primary technical driver of energy cost for TECs is operations and maintenance. This problem is deeply tied to the reliability of TECs and TEC components, and no single approach is sufficient to thoroughly address it. The best method of improving turbine reliability cannot be overcome by industry working alone; it requires collaboration with researchers. By centring itself around a collaborative effort between academia and device developers, the MONITOR project will be able to establish a technique for improving TEC reliability that is both well-grounded in solid research but also of meaningful use in real tidal stream industry applications. We have discussed the importance of TEC reliability to the establishment of tidal stream energy as a widespread low-carbon electricity generation technology, and in the context of a multi-faceted TEC reliability modelling project we have discussed the options that are available to us. Specifically, we have presented the five modelling approaches that are applied in the MONITOR project: a) reliability modelling, through the VMEA method; b) at-sea testing of full-scale prototype TECs; c) laboratory testing of scaled-down TEC models; d) numerical predictions of TEC performance and loads; and e) technoeconomic modelling to translate the reliability predictions into predicted impacts on the cost of energy produced.

For each of these five methods, work is ongoing, and certain aspects of the work that has already been carried out cannot be shared due to commercial sensitivity. Nonetheless, we have presented some of the preliminary data, particularly from the experimental and numerical modelling approaches. Data analysis and simulations are ongoing, but in this paper we have shown that the results already available shine some light on specific aspects of reliability. Specifically, the performance data from lab tests at different turbulence intensity levels indicates that over load variability (as measured by the standard deviation of power coefficient) appears to be quite similar across different turbines, but on the other hand is very sensitive to the turbulence intensity in the inflow. The numerical results show some divergence from the lab tests, but as discussed in section IIID we hypothesise that this is due to simplification of the rotor geometry near the blade root causing power production in overspeed to be overestimated – this means that the choice of blade root geometry is likely to be significant for controlling the load variability for turbines that use overspeed control.

As our investigation of TEC reliability proceeds, we expect to gather extremely useful data from the full-scale prototype turbine deployments; specifically, we will have simultaneous measurements of blade loads, turbine performance (including shaft loads) and environmental conditions such as marine current turbulence (by using high-frequency measurements of ocean current velocities) and waves (significant wave height, period etc.). This will yield an extremely rich data set that is not only valuable in itself, but will also allow us to validate the numerical simulations, and verify the scaling of the laboratory work. With these modelling approaches validated, we will be able to predict load variability in a wide range of environmental and operation conditions. Thence, we can give a well-grounded prediction of the impact of environmental factors on turbine load variability, and in turn predict their effects on TEC reliability and ultimately on cost. All this activity is taking place in the context of a cooperative project with both SME and academic partners, and we will continue to engage with researchers and industry throughout the project lifetime.

References

[1] ORE Catapult, "Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit", May 2018 [Online]. Available: https://ore.catapult.org.uk/reports-and-resources/reports-publications/ore-catapult-reports/

[2] S. Astariz, A. Vazques and G. Iglesias, "Evaluation and comparison of the levelized cost of tidal, wave and offshore wind energy," *J. Renew. Sustain. Ener.*, vol. 7, no. 5, 2015

[3] European Offshore Wind Industry, "Joint declaration on cost reduction", June 2016 [Online]. Available: https://gwec.net/wp-content/uploads/2016/06/160603-FINAL-Offshore-wind-cost-reduction-statement-with-annex.pdf

[4] Ove Arup & Partners Ltd., "Review of Renewable Electricity Generation Cost and Technical Assumptions", June 2016 [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566718/Arup_Renewable_Generation_Cost_Report.pdf

[5] C. M. Johnstone, D. Pratt, J. A. Clarke and A. D. Grant, "A techno-economic analysis of tidal energy technology," *Renew. Energ.*, vol. 49, pp. 101-106, 2013.

[6] A. D. Sagar and B. van der Zwaan, "Technological innovation in the energy sector: R&D, deployment and learning-by-doing," *Energ. Polivy*, vol. 34, no. 17, pp. 2601-2608, 2006

[7] P. Johansson, A. Chakhunashvili, S. Barone and B. Bergman, "Variation Mode and Effect Analysis: a Practical Tool for Quality Improvement," *Qual. Reliab. Eng. Int.*, vol. 22, pp. 865-876, 2006

[8] B. Polagye and J. Thomson, "Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, WA (USA)," *Proc. Inst. Mech. Eng. Pt A: J. Pow. Ene.*, vol. 227, no. 3, pp. 352-367, 2013

[9] B. Gaurier, G. Germain, J. V. Facq, C. M. Johnstone, A. D. Grant, A. H. Day, E. Nixon, E. Di Felice and M. Costanzo, "Tidal energy "Round Robin" tests comparisons between towing tank and circulating tank results." *Intl. J. Mar. Energ.*, vol. 12, pp. 87-109, 2015

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

[11] M. Togneri, I. Masters, C. Carlier, C. Choma Bex and G. Pinon, "Comparison of synthetic turbulence approaches for two numerical tidal turbine models," in *Proceedings of the 12th European Wave and Tidal Energy Conference*, 2017

[12] M. O'Connor, T. Lewis and G. Dalton, "Operational expenditure costs for wave energy projects and impacts on financial returns," *Renew. Energ.*, vol. 50, pp. 1119-1130, 2013

[13] A. Chakhunashvili, P. M. Johansson and B.L. Bergman, "Variation mode and effect analysis", in *Proceedings of the Annual Reliability and Maintainability Symposium*, 2004

[14] S. J. Morrison, "Variance synthesis revisited." *Qual. Engin.*, vol. 11, no. 1, pp. 149-155, 1998

[15] B. Bergman, J. De Maré, T. Svensson and S. Loren eds., *Robust design methodology for reliability: Exploring the effects of variation and uncertainty.* John Wiley & Sons, 2009.

[16] R. Karsten, J. McMillan, M. Lickley and R. Haynes, "Assessment of tidal current energy in the Minas Passage, Bay of Fundy", *Proc. Inst. Mech. Eng. Part A: J Power Energ.*, vol. 222, pp. 485-492, 2008

[17] B. Polagye, M. Kawase and P. Malte, "In-stream tidal energy potential of Puget Sound, Washington", *Proc. Inst. Mech. Eng. Part A: J Power Energ.*, vol. 223, pp. 571-587, 2009

[18] T. A. A. Adcock, S. Draper, G. T. Houlsby, A. G. L. Borthwick and S. Serhadlıoğlu, "The available power from tidal stream turbines in the Pentland Firth," in *Proc. R. Soc. A*, vol. 469, 2013

[19] J. Thomson, B. Polagye, V. Durgesh and M. C. Richmond, "Measurements of turbulence at two tidal energy sites in Puget Sound, WA", *IEEE J Ocean Eng*, vol. 37, pp. 363-374, 2012

[20] M. Togneri, M. Lewis, S. Neill and I. Masters, "Comparison of ADCP observations and 3D model simulations of turbulence at a tidal energy site", *Renew. Energ.*, vol. 114, pp. 273-282, 2017
[21] J. Thake, IT Power, "Development, Installation and Testing of a Large-Scale Tidal Current Turbine", October 2005 [Online]. Available: https://webarchive.nationalarchives.gov.uk/20100104180025/http://www.berr.gov.uk/files/file18130.pdf
[22] J. A. C. Orme and I. Masters, "Design and testing of a direct drive tidal stream generator," *Proc. Inst. Marine Engin. Sci. Tech. Part B: J. Marine Des. Oper.*, vol. 9, 2005
[23] P. Jeffcoate, B. Elsaesser and T. Whittaker, "Testing Tidal Turbines – Part 1: Steady towing Tests vs. Tidal Mooring Tests," in *Proceedings of the ASRANet International Conference on Offshore Renewable Energy*, 2014
[24] P. Jeffcoate, R. Starzmann, B. Elsaesser, S. Scholl and S. Bischoff, "Field measurements of a full scale tidal turbine," *Int. J. Marine Energ.*, vol. 12, pp. 3-20, 2015
[25] ocean_2g, "Review and conclusions of prototype testing in control environment", (internal report) D1.4, 2018
[26] A. Pacheco, E. Gorbeña, T. A. Plomaritis, E. Garel, J. M. S. Gonçalves, L. Bentes, P. Monteiro, C. M. L. Afonso, F. Oliveira, C. Soares, F. Zabel and C. Sequeira, "Deployment characterization of a floatable tidal energy converter on a tidal channel, Ria Formosa, Portugal." *Energy*, vol. 158, pp. 89-104, 2018
[27] A. Pacheco, Ó. Ferreira, R. Carballo and G. Iglesias, "Evaluation of the tidal stream energy production at an inlet channel coupling field data and modelling", *Energy* vol. 71, pp. 104-117, 2014
[28] E. González-Gorbeña, A. Pacheco, T. A. Plomaritis, O. Ferreira, C. Sequeira, "Estimating the optimum size of a tidal array at a multi-inlet system considering environmental and performance constraints," *App. Energy*, vol. 232, pp. 292-311, 2018
[29] J. Harrison, "ReDAPT MC7.3 Public Domain Report: Final", Energy Technologies Institute, August 2015 [Online]. Available: https://www.eti.co.uk/programmes/marine/redapt
[30] J. McNaughton, S. Harper, R. Sinclair and B. Sellar, "Measuring and Modelling the Power Curve of a Commercial-Scale Tidal Turbine", in *Proceedings of the 11th European Wave and Tidal Energy Conference*, 2015
[31] S. G. Parkinson and W. J. Collier, "Model validation of hydrodynamic loads and performance of a full-scale tidal turbine using Tidal Bladed," *Int. J. Mar. Energ.*, vol. 16, pp. 279-297, 2016
[32] U. Ahmed, D. D. Apsley, I. Afgan, T. Stallard and P. K. Stansby, "Fluctuating loads on a tidal turbine due to velocity shear and turbulence: Comparison of CFD with field data," *Renew. Energ.*, vol. 112, pp. 235-246, 2017
[33] A. S. Bahaj, A. F. Mollan, J. R. Chaplin and W. M. J. Batten, "Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank", *Renwe. Energ.*, vol 32., pp. 407-426, 2007
[34] A. Mason-Jones, D. M. O'Doherty, C. E. Morris, T. O'Doherty, C. B. Byrne, P. W. Prickett, R. I. Grosvenor, I. Owen, S. Tedds and R. J. Poole, "Non-dimensional scaling of tidal stream turbines", *Energy*, vol. 44, pp. 820-829, 2012
[35] L. E. Myers and A. S. Bahaj, "Experimental analysis of the flow field around horizontal axis tidal turbines by use of scale mesh disk rotor simulators", *Ocean Eng.,* vol 37, pp. 218-227, 2010
[36] T. Stallard, T. Feng and P. K. Stansby, "Experimental study of the mean wake of a tidal stream rotor in a shallow turbulent flow", *J. Fluid Struct.,* vol. 54, pp. 235-246, 2015
[37] T. Stallard, R. Collings, T. Feng and J. Whelan, "Interactions between tidal turbine wakes: experimental study of a group of three-bladed rotors", *Philos. T. Roy. Soc. A*, vol. 371, 2013
[38] D. R. J. Sutherland, D. R. Noble, J. Steynor, T. Davey and T. Bruce, "Characterisation of current and turbulence in the FloWave Ocean Energy Research Facility", *Ocean Eng.*, vol. 139, pp. 103-115, 2017
[39] D. Sutherland, S. Ordonez-Sanchez, M. R. Belmont, I. Moon, J. Steynor, T. Davey and T. Bruce, "Experimental optimisation of power for large arrays of cross-flow tidal turbines", *Renew. Energ.*, vol. 116, pp. 685-696, 2018
[40] B. Gaurier, P. Davies, A. Deuff and G. Germain, "Flume tank characterization of marine current turbine blade behaviour under current and wave loading", *Renew. Energ.*, vol. 59, pp. 1-12, 2013
[41] P. Mycek, B. Gaurier, G. Germain, G. Pinon and E. Rivoalen, "Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: One single turbine", *Renew. Energ.*, vol. 66, pp. 729-746, 2014
[42] P. Mycek, B. Gaurier, G. Germain, G. Pinon and E. Rivoalen, "Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part II: Two interacting turbines", *Renew. Energ.*, vol. 68, pp. 876-892, 2014
[43] M. Lewis, S. P. Neill, P. E. Robins and M. R. Hashemi, "Resource assessment for future generations of tidal-stream energy arrays", *Energy*, vol. 83, pp. 403-415, 2015
[44] M. Edmunds, R. Malki, A. J. Williams, I. Masters and T. N. Croft, "Aspects of tidal stream turbine modelling in the natural environment using a couple BEM-CFD model", *Int. J. Marine. Energ.*, vol. 7, pp. 20-42, 2014
[45] W. M. J. Batten, A. S. Bahaj, A. F. Molland and J. R. Chaplin, "Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines", *Ocean Engin.*, vol. 34, no. 7, pp. 1013-1020, 2007
[46] I. Masters, J. C. Chapman, M. R. Willis and J. A. C. Orme, "A robust blade element momentum theory model for tidal stream turbines including tip and hub loss corrections", *J. Marine Engin. Tech.*, vol. 10, no. 1, pp. 25-25, 2011
[47] J. C. Chapman, I. Masters, M. Togneri and J. A. C. Orme, "The Buhl correction factor applied to high induction conditions for tidal stream turbines", *Renew. Energ.*, vol. 60, pp. 472-480, 2013
[48] G. Pinon, P. Mycek, G. Germain and E. Rivoalen, "Numerical simulation of the wake of marine current turbines with a particle method", *Renew. Energ.*, vol. 46, pp. 111-126, 2012
[49] P. Mycek, B. Gaurier, G. Germain, G. Pinon and E. Rivoalen, "Numerical and experimental study of the interaction between two marine current turbines", *Int. J. Marine Energ.*, vol. 1, pp. 70-83, 2013
[50] G. Dalton, G. Allan, N. Beaumont, A. Georgakaki, N. Hacking, T. Hooper, S. Kerr, A. M. O'Hagan, K. Reilly, P. Ricci, W. Sheng and T. Stallard, "Economic and socio-economic assessment methods for ocean renewable energy: Public and private perspectives", *Renew. Sust. Energy Rev.*, vol. 45, pp. 850-878, 2015.
[51] G. Pinon, C. El Hadi, M. Slama, J. Nuño, P. Mansilla, E. Nicolas, J. Marcille, J-V. Facq, I. Belarbi, B. Gaurier, G. Germain, A. Pacheco and M. Togneri, "Influence of turbulence and wave flow conditions on different scaled tidal turbines," in *Proceedings of the 14th European Wave and Tidal Energy Conference*, 2019
[52] Ocean Energy Europe, "Industry Vision Paper", April 2013 [Online]. Available: http://www.oceanenergy-europe.eu/images/Publications/European_Ocean_Energy-Industry_Vision_Paper_2013.pdf
[53] DG MARE, "Blue Growth: Scenarios and drivers for Sustainable Growth from the Oceans, Seas and Coasts", March 2012 [Online]. Available: https://ec.europa.eu/maritimeaffairs/publications/blue-growth-scenarios-and-drivers-sustainable-growth-oceans-seas-and-coasts_en