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Application of VMEA to assess uncertainties affecting tidal devices: preliminary findings using tank-scale turbines.

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ABSTRACT: This paper presents initial findings from the application of Variation Mode and Effect Analysis (VMEA) to two tidal energy devices, in the context of the MONITOR (*Multi-Model Investigation of Tidal Energy Converter Reliability*) project. VMEA is an engineering tool used to identify and understand sources of variation or uncertainty, which could affect reliability of a device or component. Understanding and controlling sources of variation can allow identification of methods to reduce their impact and improve reliability. In this work we consider uncertainties affecting loading on the blades of tidal turbines. Results from tank scale testing of two different turbines are used to investigate the sensitivity of blade loading to a range of uncertainties, including inflow velocity, turbulence intensity, operating speed, and blade geometry. Initial learnings from the application of VMEA to tidal devices are discussed.

1 INTRODUCTION

The reliability of tidal energy converters (TEC) remains a key issue to be solved to enable further growth of the sector and reduce investment risks and the cost of generation. The MONITOR project (Togneri et al. 2019) is working with industry to develop tools for use by tidal developers to investigate and improve device reliability. The project takes a multi-model approach to the problem of reliability, and will combine numerical modelling, scale (tank test) modelling and at-sea modelling results into a Variation Mode and Effect Analysis (VMEA) model. Results from this will then be fed into a techno-economic model. At present laboratory testing has been completed, numerical and at-sea modelling is underway, a first iteration of the techno-economic model has been built, and the VMEA model is in development.

Fixed and floating prototype devices belonging to Sabella and Magallanes Renovables respectively have been chosen for study in the project. Sabella's 5-bladed, 500 kW fixed-bottom D12 tidal turbine is fixed pitch and yaw. Their 6-bladed, 1MW D10 turbine has previously been deployed in Fromveur Strait, Ushant Island, Brittany. Magallanes Renovables' floating ATIR platform is a 1:1 scale prototype 2MW turbine with two contra-rotating rotors suspended below the device's hull. The device can yaw passively, and blades pitch for operation in both tidal

directions. It is installed at the full-scale tidal test site at the European Marine Energy Centre (EMEC) and the full-scale prototype has now reached TRL9 following a grid-connected testing programme.

This paper will focus on the VMEA component of the project. A background and overview of the VMEA process is given, and then application of the process to scale-models of the ATIR and D12 devices is discussed.

2 VARIATION MODE & EFFECT ANALYSIS

VMEA was developed as an extension to the failure mode and effect (FMEA) process (Johansson, 2006) as a result of the conclusion that the majority of failures seen are caused by unexpected or uncontrolled variances. By understanding and controlling these variances then designs can be altered to improve robustness and reduce the risk of failure (Chakhunashvili, 2004). VMEA aims to control the impact of variances or variations by identifying and quantifying the sources of uncertainty which contribute to these variations. For example, if considering blade life, uncertainty in the material properties or blade geometry could both lead to variation in the blade strength, affecting the expected blade life. Similar is true around factors affecting the loading on the blade. For each given device or component 'key

characteristic', such as blade life, there will be a number of uncertainties leading to potential variation. Exactly what these are depends on the characteristic and on the available data. The VMEA tool provides a systematic method of assessing these uncertainties.

VMEA has previously been used to good effect in the mature automotive and aerospace industries (Efremov, 2018). The application of VMEA to marine energy converters has been previously investigated by the RiaSoR I and II projects - prior case studies on wave energy devices found that a probabilistic VMEA approach was a useful method of identifying design improvements (Johannesson 2019), and that the post-processing methodology used in load assessments is responsible for a large amount of uncertainty (Atcheson 2019). The work performed in MONITOR is the first application of VMEA to real tidal devices. This provides an opportunity to develop and test the process on two divergent tidal technologies, with the aim of generating a device agnostic VMEA tool. Blades have been selected for the first VMEA study.

2.1 Process Overview

One of the aims of MONITOR is to develop a VMEA process and tool that works for the tidal industry. VMEA is an established process with clearly defined steps, and the existing framework for VMEA developed by RiaSoR (Johannesson, 2016) is being used as a basis for development. This framework includes seven steps as set out below.

1. Target Variable Definition

This should be a particular characteristic of a critical component (likely identified via FMEA or failure mode and effect and criticality analysis FMECA), e.g. blade fatigue life. As MONITOR looks at blades and structures, we will be performing VMEA on blades and structural components for both devices prior to developing a generic tool.

2. Uncertainty Sources Identification

The target variable should be calculated (if not already done so), and all sources of uncertainty in each step of these calculations identified. Calculations should use actual expected values, rather than include safety factors or partial factors for VMEA purposes

3. Uncertainty Sensitivity Assessment

Evaluate how sensitive the target function is to the source of variation and calculate sensitivity coefficient C_i . This can be done using engineering judgement, historical data, statistical methods, numerical modelling, physical testing.

4. Uncertainty Size Assessment

Calculate the uncertainty size, S_i . This is often taken as the standard deviation of the data set in consideration.

5. Total Uncertainty Calculation

The product of each uncertainty sensitivity C_i and size S_i is calculated - the Variation Risk Priority Number (VRPN). VRPN values are summed to give a total uncertainty. The primary output of VMEA is a results table created at this stage (Table 1).

Table 1: Example VMEA Results Table

Input			Result
Uncertainty	Sensitivity	Size	VRPN
Environmental conditions	C1	S1	$C1*S1$
Operating behaviour	C2	S2	$C2*S2$
Device geometry	C3	S3	$C3*S3$
Component strength	C4	S4	$C4*S4$
Calculation methods	C5	S5	$C5*S5$
Total uncertainty			$\sum C_i*S_i$

6. Reliability and Robustness Evaluation

Examine the results to look for dominating uncertainties and calculate safety factors where needed.

7. Improvement Actions

Use the results to identify items for investigation or improvement.

There are three widely acknowledged types or levels of VMEA which all follow the same steps. These are Basic, Enhanced, and Probabilistic and the type performed depends on the stage in the design process and the information available. The MONITOR project aims to develop a tool for probabilistic VMEA.

2.2 Basic VMEA Results

An initial basic VMEA study was previously carried out as part of MONITOR using the target function of blade life. In the basic VMEA the nominal blade life was not calculated, but sources of uncertainty were identified which could influence blade life calculations. A total of 20 uncertainty sources were split into categories of design uncertainties, modelling uncertainties, and operational uncertainties. Qualitative assessment based on professional engineering expertise was used to determine which factors were most likely to influence the accuracy of blade life calculations, by scoring the size and sensitivity of each uncertainty on a scale of 1-10. This was done by a group of multidisciplinary engineers, and with input from developers to draw on past experience. A group approach is recommended to improve process robustness, as the absence of historical reference data in relatively immature industries such as tidal power is one of the challenges of implementing the VMEA process. The size and sensitivity values assigned to each variable differed between the ATIR and D12 devices, for example the ATIR device is affected by wind

loading, whilst the D12 is not. However, the results of the VMEA showed the uncertainty sources of most significance were the same for both devices – this could be influenced by the engineers’ views, but is also reflective of the types of data most frequently available when assessing tidal device loading. The uncertainties with the highest VRPNs (in no particular order) were:

- Material strength
- Manufacturing repeatability
- Site environmental variations
- Anomaly loads (e.g. impacts / storm loading)
- Life model estimation and assumptions
- Damage model errors
- Wave load estimations
- Turbulence loading influence

The results of this initial VMEA were used to support specification of device instrumentation, and as a baseline for development of more detailed enhanced and probabilistic VMEA models.

3 DESIGN CASE

Experimental data from flume tank trials carried out at IFREMER is being used in the current stages of VMEA tool development. Experiments were designed to focus on the influence of varying inflow parameters on blade loading based on finding from the initial VMEA, and to enable comparison with a blade element momentum theory (BEMT) model which will be used later in the project alongside full-scale device data. As the project progresses, the VMEA will incorporate these BEMT and at-sea datasets in order to build a robust tool. The studies in MONITOR will cover both blade and structural components. The work presented here considers blades only.

The flume tank trials were carried out using a 1:28 scale model of the ATIR rotor and 1:20 model of the D12 rotor. Torque and thrust measurements were recorded, and additional load cells were used to measure blade root forces in x and y directions, and blade root bending moments in the x, y, and z directions. These were recorded at a frequency of 120Hz under operation in a series of different conditions. In all cases the tank conditions were allowed to settle prior to recording, and the test was then run for several minutes at constant conditions. Full details of the test setup can be seen in (Pinon, 2019).

The adimensional power and thrust coefficient - C_P^* and C_T^* - curves for the two scale turbines for a range of inflow conditions, with and without waves present have previously been reported in (Pinon et al, 2019). The influence on standard deviations of the power and thrust coefficients are also reported. The devices were run at a range of tip speed ratios (TSR),

and the operating range of the scale devices indicated as $3.75 \leq \text{TSR} \leq 5$ (D12) and $4 \leq \text{TSR} \leq 5.5$ (ATIR).

3.1 Baseline Operating Conditions

In order to define a baseline set of tank conditions to use in the current analysis and VMEA, the real site conditions and Froude scaling characteristics were considered. A summary of full scale device characteristics are given in Table 2, however site conditions are confidential and cannot be shared.

Table 2: D12 and ATIR Characteristics

	D12	ATIR
Device power	500kW	1.7 MW
Rotors	Single rotor	Dual (contrarotating)
Rotor diameter (m)	12	19
Approx. blade length (m)	4	8.5
Blades per rotor	5	3
Blade pitching	Fixed	2-oriented
Rated rotor RPM	10-20	16
TSR below rated	4.5	6.7
Yaw	Fixed	Passive, moorings
Support Structure	Bottom fixed – gravity	Floating – chain moored
Prototype location	Fromveur Strait, Ushant Island	EMEC, Fall of Warness
Hub height	13m from seabed	14m sub surface
Site depth (m)	55	50

Tank testing parameters are shown in Table 3, along with the selected baseline parameters. The inflow speed is chosen as 1m/s. This is based on it being most representative of site flow speeds using Froude scaling, however it is important to also bear in mind that the influence of Reynolds number is greater below flow speeds of 1.2m/s (Pinon 2019). A TSR of 5 is selected as this is close to the peak operational performance on both scale devices. Turbulence data has not been analysed for either device yet as part of this project, but previous studies at EMEC have observed a turbulence intensity (TI) of 16.7% in flood tide (Sellar, 2020). Measurements at another tidal site, in Shetland, found typical values for TI of 12 – 20% in fast tidal flow regions (Macleod, 2019). For this reason a TI of 15% has been selected for the baseline conditions. Waves have not been considered in the baseline case and wave influence will be studied in more detail later in the project.

Table 3: Tank Test Parameters and Selected Baseline Conditions

	U [m/s]	TI [%]	TSR	Wave amplitude [m]	Wave frequency [Hz]
Range	0.8 – 1.4	1.3, 3.7, 15	0-6 D12 0-8 ATIR	0.095, 0.13	0.5, 0.7
Baseline	1	15	5	-	-

3.2 Blade Root Bending

In this study we focus on recorded blade root bending moments to investigate the influence of operating parameters on blade loading. A sensitivity analysis study of tidal turbine loads (Nevalainen, 2016) has shown that out-of-plane rotor bending moments transmit into the drive train and affect shaft loading as well as the blades themselves due to uneven loading across the full rotor. Scale studies have shown that fluctuations in bending moments are strongly linked to rotor loads (Blackmore, 2016) and increased TSR and TI increase load fluctuations. Analysis of frequency variation in unsteady rotor loading using BEMT (Payne 2018) has shown that TI changes the frequency loading peaks and which harmonics peaks are present at.

(Galloway 2014) have found that device yaw has a significant influence – something which is not covered in this paper but will be considered later in the project, as this could particularly influence the fixed-base D12 device.

Unsteady loading is critical to blade root bending moments, particularly out-of-plane bending, and it is bending moments in this flapwise direction (My) that are the main focus of this study. Edgewise bending moments (Mx) are more driven by inertial and gravitational loads and in tidal turbines are significantly lower than My. (Galloway 2014) found that My is 9.5 times Mx (in waves), and the loading range is 175% of median.

For the experimental tests carried out, there are results for a single blade on the D12 scale model, and for all three blades on the ATIR scale model. For this study we will focus on recorded loading on blade 1 only, with the assumption that loading behavior is similar for all blades, and the lengths of the test runs are sufficient to capture this behavior on a single blade. In Figure 1 nondimensionalised My1 and Mx1 bending moments and calculated resultant bending moments (Mres1) for blade 1 are shown, for inflow conditions of $U=1$ m/s and $TI=15\%$. These have been nondimensionalised using the maximum values of My1 for each device. As expected, the My1 values are significantly higher than Mx1, and are very close to resultant bending moments, giving confidence in the approach to focus on My1. It can be seen that My1 peaks at $TSR=5$ for the D12 device, but not the ATIR device.

Time series My1 data for a representative 10 second period is shown in Figure 2 for both D12 and ATIR devices at $TSR=5$ for four different inflow speeds at two different turbulence intensities. As expected, the variation in bending moments is seen to increase with both turbulence intensity and with flow speed for both devices. The mean bending moment increases with flow speed, but does not change significantly with increased turbulence. The overall range of bending moment increases with both U and

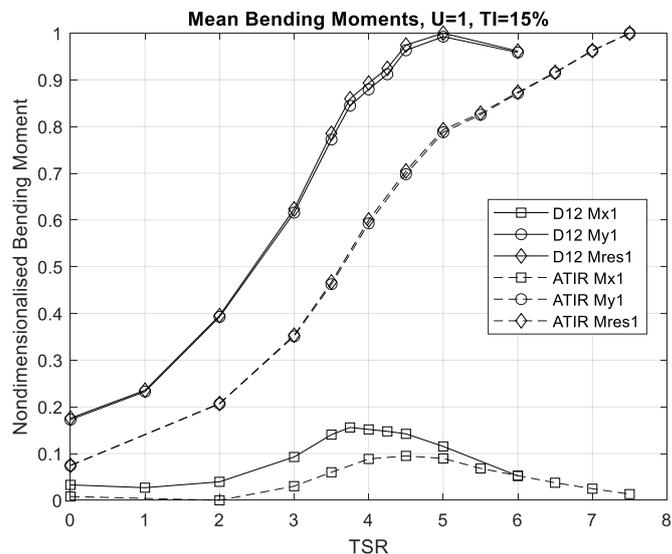


Figure 1: Mean edgewise (Mx1), flapwise (My1) and resultant (Mres1) bending moments for scale D12 and ATIR devices at $U=1$ m/s, $TI=15\%$

TI, but the lower the inflow velocity, the higher the fluctuation as a percentage of the mean value. For example, the bending moment fluctuation in relation to the mean value ranges for the D12 from 14% (at $U=1.4$, $TI=1.3$, $TSR=5$) to 166% ($U=0.8$, $TI=15$, $TSR=5$). The out-of-plane bending moments recorded on the ATIR are in the region of twice those recorded on the D12.

4 APPLICATION OF VMEA TO ATIR AND D12

A second pass of the VMEA process is now being carried out using the tank test data. As the project progresses and more data is available, the VMEA models for the two devices will be further refined – this will both make the VMEA model more accurate, and will also give a good understanding of industry considerations for using the VMEA process with a range of different data sets. This section of the paper describes some of the work done to date. Exactly how VMEA is applied is open to interpretation, and the ‘best’ method is not yet known. Hence, various methods of performing the analysis for the VMEA have been tested and these are discussed.

4.1 Target Function Definition

Selection of the target function is the first step of the VMEA process and defines the parameter or property of interest. The blade has been selected as the component of interest, but it must also be determined what property of the blade is most important – this could be expected life, or total damage for example. In this case the out-of-plane fatigue loading on the blades has been selected as the function of interest. Often the target function will be defined as a limit statement which includes both strength and load, but in this case

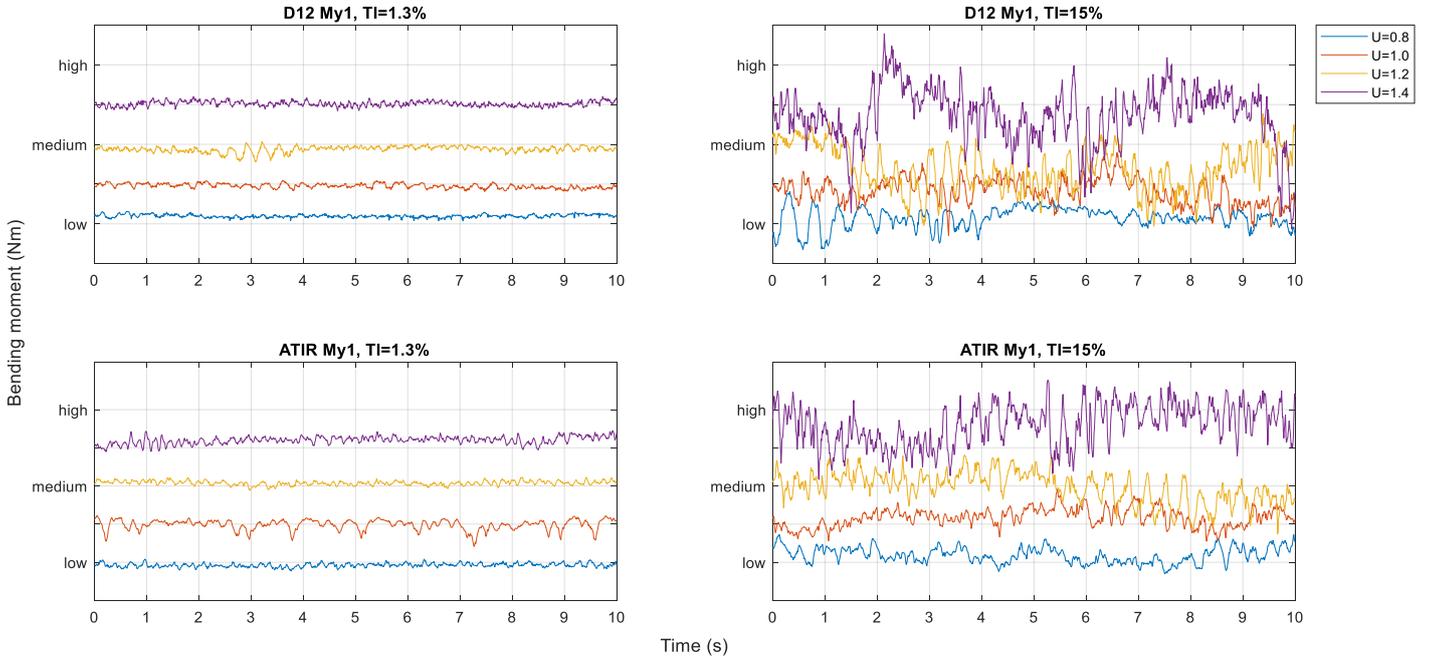


Figure 2: Flapwise (M_{y1}) bending moments for a range of inflow speeds at $TSR = 5$.
 Top left: D12, $TI = 1.3\%$; Top right: D12, $TI = 15\%$; Bottom left: ATIR, $TI = 1.3\%$; Bottom right: ATIR, $TI = 15\%$

the information to determine blade strength is not known, and so solely loading is focused on. Ultimate loads are also of interest in the project, and extreme loading will be considered at a later date.

Out of plane fatigue loads, M_y , on blade 1 are being considered, and in this case calculating the equivalent damage done to a blade due to fatigue loading via calculation of DEL has been chosen. This could be extended to calculate expected blade life if information on blade strength was available, but for this study we want to solely look at the uncertainties related to calculating fatigue damage.

4.2 Calculation of Baseline Target Function

Once the target function is selected, the next step is to calculate the expected value for the function. Many wave and tidal standards will describe methods for calculating expected life or expected damage which incorporate conservatism into the calculation, but for VMEA the *most likely, expected* values with no safety factor should be used.

To calculate the DEL the equation from the Tidal Bladed theory manual (Garrad Hassan, 2015) was used, using the rainflow count methodology and summing the number of cycles at each load range. This equation calculates the equivalent load over the same number of cycles which would cause the same damage as the varying amplitude load cycles experienced in reality. In this case C refers to the number of load cycles which were counted in the baseline case – $U=1, TI=15\%, TSR=5$.

$$DEL = \left(\frac{\sum_i n_i S_i^m}{C} \right)^{\frac{1}{m}} \quad (1)$$

The m -value refers to the negative gradient of an S-N fatigue curve for the blade material. The scale D12

and ATIR blades were manufactured from composite and aluminium respectively, so m -values of 12 for the composite material, based on typical range between 10 and 14, (Mandell, 1997) and 7 for aluminium, (British Standards Institution, 2007) have been used.

Typically the DEL is calculated using stress values, although as highlighted in (McCann 2007), stress depends upon geometry and is assumed proportional to load, so it is acceptable to use load in respect of stress. NREL have also developed a modified version with M-N curves and recorded bending moments (Freebry, 2000), such that details of blade strength and geometry are not required for the calculations. In this case the VMEA sensitivity study has been performed twice with this equation, once using recorded bending moment M_{y1} , and once using calculated stresses from recorded F_{x1} values and approximate blade root cross sectional areas. The reason for this was to determine the influence on the VMEA study of each method. The full time history for each tank test run was used in the calculations.

The baseline calculated damage equivalents, \overline{DEL} , for each device cannot be shared for confidentiality reasons, but they are different for each device. The \overline{DEL} values calculated using M_{y1} are very similar between devices, despite the recorded $M_{y1\mu}$ on the ATIR being approximately 120% larger than the M_{y1} mean for the D12 under baseline conditions. Using stresses, the \overline{DEL} value calculated for the ATIR is just 35% of that for the D12, while the $F_{x1\mu}$ for the ATIR is 230% of that for the D12. The large differences in these values is due to several factors – different turbine operating curves, different blade shapes and materials, differences in load and moment fluctuations with respect to mean loading, and different methods of estimating blade cross sectional area.

4.3 Uncertainty Identification

The next step is to identify the uncertainties in the calculation of the target function, in this case \overline{DEL} . Uncertainty sources are often defined as scatter (e.g. in the case of material strength), statistical uncertainties, or model uncertainties. As the same methodology is being applied to both turbines, the sources of uncertainty are the same. Generally in practice the available data and the device of interest will mean that the uncertainty sources differ – for example when BEMT data is incorporated into the VMEA there will be modelling uncertainties, and when full scale prototype device data is incorporated the uncertainties will differ from site to site dependent on available instrumentation. The uncertainties relating to the baseline calculation are described below.

4.3.1 Appropriate selection of baseline conditions

Uncertainty relating to whether the appropriate baseline conditions have been selected is due to two main factors: a) uncertainty in site conditions, and b) uncertainty in tank scaling effects. This can be split further into uncertainty around inflow speed, turbulence intensity, and TSR. Wave conditions would also be included in this category if waves were considered in the study, and for the final VMEA we intend to.

The inflow speed will vary dependent on shear profile and turbine position in the water column. For full-scale calculations where site conditions were being used then uncertainty sources would also use (for example) site variations, hydrodynamic model errors where used. For this case U, TI and TSR values are used.

4.3.2 Damage Equivalent 'm' value

The m-value chosen will affect the results. Whilst use of 12 for carbon fibre is typical, the exact value will vary dependent on the material properties. For aluminium the values vary more widely. In both cases the m-value is an approximation, and how closely it matches the real behaviour of the blade material will affect the accuracy of the calculation results.

4.3.3 Method of calculating 'C' number of cycles

The number of load cycles identified in the baseline calculation was used throughout as the number of cycles over which to calculate the equivalent load amplitude. Another potential approach is to calculate the equivalent load for a set period of operation, or to recalculate the number of load cycles for each set of conditions.

4.3.4 Use of My1 or stress calculated from Fx1

Two approaches to calculating the damage equivalent have been used, and the effect of using My1 rather than calculated stress is not known but will introduce further uncertainties, as the m-value is for an S-N curve rather than an M-N curve.

4.3.5 Blade geometry

The cross-sectional geometry of both blades has been calculated based on theoretical blade sections and this introduces uncertainty. The exact as-manufactured geometry will differ from this.

4.3.6 Pre-processing of data

The raw data signals of My1 and Fx1 were used in the calculation, and this will introduce some noise which is not a true reflection of the loading experienced. In future it is likely that the load signal will be preprocessed but an appropriate filter threshold is not yet understood.

4.3.7 Uncertainties not directly linked to DEL calculation

Operational strategies will also have an influence on the effect of uncertainties, but these were not considered in the current VMEA, for example the control methodology. It has been shown by (Milne, 2016), that that unsteady loads with stall regulated turbines are larger due to separation of boundary layer. This separation is also seen at low tip speed ratios. Recent tow-tank testing of a scale turbine in waves under two control strategies also found that increased bending moment fluctuation was observed more in cases with torque control rather than thrust control (Ordonez - Sanchez 2019).

There are potential uncertainties with regards to the accuracy of the recorded data, although the data has been modified to account for ambient load readings.

A more general uncertainty when using recorded loads from tank testing is how well these can be scaled to be representative of the full-scale behavior. In this case no attempt to scale the loads has been made, only to use the recorded loads to understand the impact of different uncertainty sources on the loading behavior. It is hoped that through comparison with tank-scale and full-scale BEMT results in the next stage of the project the suitability of using tank scale loading for VMEA can be proven.

4.4 Uncertainty Sensitivity

Once uncertainty sources have been identified the sensitivity should be quantified, as per step 3 of the VMEA process set out in Section 2.1. There are typical ways to do this as part of a VMEA study, but other approaches have also been taken regarding parameters influencing tidal turbine loading. Parametric studies have been carried out by (Milne, 2010), and (Nevalainen 2016) considering the effect of inflow parameters on blade loads using BEMT. The former found waves, site depth and shear to have significant influence while the latter also included turbine geometric parameters and found blade root pitch and rotor radius to be influential. (McCann, 2007) has looked at the sensitivity of fatigue loading due to

surface waves and TI, and incorporated 50 year extreme loading to consider the criticality of damage caused by fatigue.

Sensitivity in VMEA is often found by calculating the target function twice, once with expected values and the other with one parameter two standard deviations away from expected value. The sensitivity coefficient is then the difference between these two values, divided by two standard deviations (Johannesson 2016). Another approach is to calculate the partial derivative of the target function with respect to the uncertainty source.

In the current example in many instances the standard deviation is not known, and there is not a known equation relating the target function to the uncertainty source and so a different approach has been taken. The target function has been calculated multiple times changing one factor relating to an uncertainty at a time. The percentage deviation of the new value from DEL has then been calculated. The changes in DEL can be seen in Table 4 for each device, for both calculation methods (My1 and stress). It can be seen that the difference in values between the two methods was small (typically 1-2%). The values for the ATIR and D12 differ but are in the same order of magnitude, other than for the m-values, but this is due to different starting m-values. A ‘prefiltered’ change is shown, but this is not included in the VMEA going forward as the preprocessing method needs more consideration, as it cannot currently be quantified in terms of change to the original data set.

Table 4: Percentage change from calculated baseline DEL

	Change in DEL (using My1)		Change in DEL (using stress)	
	%		%	
	D12	ATIR	D12	ATIR
m = 11	-5	41	-5	41
m = 7	-30		-31	
m = 12		49		49
TI = 3.7	-62	-59	-62	-62
TI = 1.3	-78	-58	-77	-64
TSR = 3	-46	-44	-47	-40
TSR = 4	-25	-19	-23	-18
U = 0.8	-39	-30	-40	-34
U = 1.2	41	46	39	50
U = 1.4	96	95	98	104
Prefiltered	-40	-43	-37	-39
A = -10%			11	11
A = -20%			25	25

To then calculate a sensitivity coefficient, the difference values were related to the percentage change in the factor of interest. The difference values observed in the stress case were used for this step, with a different coefficient for each turbine. An average for each uncertainty is calculated, as the results suggest

the sensitivities are not all related linearly. The sensitivity coefficients are in Table 5.

Table 5: Sensitivity Coefficients

	D12	ATIR
m	0.67	0.7
TI	0.83	0.75
TSR	1.15	0.95
U	2.14	2.26
A	-1.15	-1.15

Reviewing the calculated sensitivity coefficients, the two devices have similar results in terms of which parameters have most impact, but there are differences between the values. These will vary more when uncertainty size is incorporated and VRPN is calculated. Flow speed is of significant impact, but in a tidal environment flow speed is generally well understood so the uncertainty size is expected to be low.

The impact of TSR is also high – this is important as the control strategy of the turbine will have a significant effect. When the VMEA incorporates at-sea test data we will be able to understand this in more detail. However, measuring loading sensitivity could be harder with device instrumentation as the devices will not have the same load cells fitted to each blade, so it is useful to be able to also study sensitivity using tank data and, as will be included later, BEMT data.

4.5 Uncertainty Size

The next step in the VMEA process is to calculate the size of each identified uncertainty source. This is done using standard deviation, by a range of methods. The size of uncertainties has not yet been quantified in this study, partly due to the fact that collection and analysis of the required data is ongoing. Typically uncertainty size is quantified using standard deviation, and there are a range of methods for calculating the standard deviation dependent on the data available (Johannesson, 2016).

More focus on uncertainty size will be included as the project incorporates BEMT and full-scale prototype results into the VMEA study. The VRPN for each uncertainty source can then be calculated and the sources with most influence on device reliability understood.

5 CONCLUSIONS AND NEXT STEPS

This work has demonstrated a methodology of calculating sensitivity coefficients for uncertainties affecting blade loading, using tank-scale data. The sensitivity coefficient calculation methodology is still in development, and increased understanding of how best to pre-process the load data is required, but the work done to date has been valuable in learning how best to apply the VMEA process and to investigate

sensitivity of the blade fatigue loading to various parameters. There are other parameters such as wave loading which will also be incorporated into the study.

Results from Swansea's SwanBEMT model will also be used to perform similar analysis both to test the process and determine how effectively tank data can be scaled up. Whilst using tank scale load data to understand the full-scale loading on a turbine is challenging due to scaling effects, it may be possible to use them in the context of a VMEA study to understand sensitivity.

The next step is to work on determining uncertainty sizes, and then calculate the VRPN for each uncertainty from the product of uncertainty size and sensitivity. It is likely preferable to focus on quantifying the uncertainty size for full-scale prototype devices, rather than the tank data as this will give us a greater understanding of uncertainties in operation.

Other potential additions to the model include:

- Extension to include the effect of fluctuation around the mean – the DEL model currently considers fatigue cycles but not the impact of the mean value.
- Consideration of turbulence length scales as well as intensity.
- The effects of transient conditions such as blade acceleration, turbine stops.
- Considering the effects of yawed flow, particularly for the fixed base model
- Understanding the impact of rotor position in the water column and shear profile.

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