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A COMPARISON OF THE INFLUENCE OF USING EMPIRICAL OR MATHEMATICALLY PRE-DEFINED WAVE ENERGY SPECTRA FOR TOWER BASE BENDING FATIGUE CALCULATIONS

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ABSTRACT
In the structural design of Floating Offshore Wind Turbines (FOWT), fatigue plays a critical role in determining the final design of the system. The fatigue loads are the result of combined aerodynamic and hydrodynamic forces acting on the elastic structure. The industry standard approach for assessing the fatigue loads involves grouping the environmental conditions into bins. These conditions include wind speed and direction, wave height, period and direction and the sea state spectral shape. In shallow seas with limited fetch the JONSWAP spectrum, or a JONSWAP-derived spectrum, is normally fitted to the site conditions and used, which also includes a peak enhancement factor (GAMMA) in a range defined by the significant wave height and peak period. However, this adjustment is sensitive to the parameter fitting process, while the vital Peak Enhancement Factor (gamma) parameter is commonly chosen as an arbitrary empirical value in the given range.

In this paper, we examine how the calculation of bending fatigue of the tower base of the IEA 15MW open source turbine supported by the UMaine VolturnUS semi-submersible is influenced by either the use of empirical spectra (measured or simulated for the specific site) against pre-described site-fitted formulas for spectral shape, and the use of different spectra per hourly sea state against a single spectrum per data bin.

The results indicate an influence of both the used spectral shape as well as the use of spectra for each sea state instead of a single spectrum per bin of data.

1. INTRODUCTION
To achieve carbon neutrality and net-zero goals, many countries plan a large amount of investments on offshore wind. Most existing offshore wind projects are ‘fixed’, with the foundation extending from the sea level to the sea bed [1]. However, the industry is moving towards applications in deeper waters for numerous reasons, such as lack of available space [2], arising issues of potential visual and acoustic pollution for local communities and the fact that wind energy is more predictable and stronger in deeper waters. Approximately 80% of the global exploitable wind energy being available for depths of more than 60 meters [3]. However, in these depths, fixed offshore wind turbines become economically unprofitable and/or technically infeasible. Other solutions such as floating offshore wind turbines (FOWT) have emerged to overcome these limitations [1].

During the design phase of FOWT, calculation of dynamic loads and responses are critical, are usually approached with computer aided engineering tools [4]. The FOWT are expected to operate in cyclic loading conditions for 20-25 years, and fatigue can play a critical role in the design and maintenance of key components of the structure [2]. Accumulated fatigue damage can be calculated with various methods, with the most commonly used being Rainflow counting for the characterisation of stress ranges and number of loading cycles, to be then introduced to the Palmgren-Miner Rule and the respective S-N curve ([5], [2]). The estimation of the S-N curve corresponding to the component study can be defined by various standards and recommended practices, such as the recommended practice DNV-RP-C203 [6], IEC 61400-3-2[7] or the Eurocode EN 1993-1-9 [8]. In these standards, according to the specific type of component and its environmental conditions different S-N curves are specified with various methods depending on the standard, which can nonetheless can be correlated to each other.

A crucial factor of the fatigue calculation process is however the estimation of the respective metocean conditions that will cause the dynamic loading and movements. The standard method for loads analysis throughout the project lifetime, is to group the metocean data into bins and simulate the bins whose probability of occurrence is above a certain threshold, as is described in numerous standards such as IEC 61400-3-2 [7]. These sea states are usually characterised by wind speed, significant wave height, wave peak period, current speed and the respective directions of wind, wave and current. Finally, another key wave parameter is the distribution of energy over the different wave periods for a given sea state.

There are various models that attempt to approach this energy distribution, with the most commonly used spectrum being the JONSWAP spectrum, which is directly related to the also common Pierson-Moskowitz spectrum, or the JONSWAP derived Torsethaugen spectrum ([9],[10]). However, the use of standardised spectra, although a necessary choice when no other data are available, has been shown to have significant effects on vital predictions for a project. Prendecast et al. [10] have shown that site specific measured spectra led to different estimation of wave energy converters (WEC) power output when compared with the use of JONSWAP or Bretschneider spectra. However, to the author's knowledge, no such study has been conducted on the effect of measured against standardised spectra for the fatigue calculation of semi-submersible floating offshore wind turbines.

This paper deals with the influence of using standardised spectra against site specific measured or simulated spectra on the estimation of accumulated fatigue on the Tower Base of a semi-submersible FOWT due to bending and axial forces.

This study is meant to be a proof of concept for two approaches:

- The use of site specific spectra (derived directly from site measurements or site hindcast simulations) against the use of pre-described mathematical formulas of spectrafitted to the site conditions. From this point these will be referred to as 'Empirical Spectra' and 'Fitted Spectra' respectively
- The use of different spectra per hourly sea state against one overall spectrum for each group of metocean conditions (bin). The latter will be referred to as 'General Bin Spectrum' and two sub-cases will be studied:
    1. The use of the peak enhancement factor (Gamma) value as 3.3 (the mean value of JONSWAP calculations according to DNV-RP-C205[11]
    2. The use of the proposed Gamma values by DNV-RP-C205[11]

This work is intended to be the starting point of a more in depth study of this phenomenon. For this reason, several simplifying assumptions are actively chosen, which are listed below:

- All spectra studies are conducted solely on 1D spectra
- The sea state (and thus load) calculation is conducted for 1 random seed only*[1].
- Wind speed is assumed constant and uniform and turbulence effects are neglected
- No current is taken into account

2. ENVIRONMENTAL CONDITIONS

The environmental conditions for 10 years are estimated on an hourly-averaged basis using the ANEMOC3 database [12] and obtained through the finite element power spectra calculation software TOMAWAC [13] for a point near the Atlantic coast of France.

Specifically, the outputs consist of wind speed and direction, wave direction, significant wave height and peak period, and the full directional spectrum for every hourly sea-state. In this study, the effects of spectrum directionality are not taken into account, so from every directional spectrum a 1D equivalent spectrum is calculated and waves are assumed to have a direction of 0 degrees, as will be explained in Section 3. Wind is assumed to be always aligned with waves while current is ignored.

For each year of data, the total number of hourly sea state conditions are grouped into bins. One year of data is simulated to calculate the average fatigue, assuming it represents an "average year". The wind speed is binned to 2 m/sec bins. For each given wind speed bin the significant wave height is binned with 1 m bin width. Finally, for every given Hs bin inside the wind speed bin, the peak period is binned with 1 sec bin width. Although the maximum bin width for Hs and Tp is set at 0.5 by the IEC 61400-3-2 [8], in this proof of concept study wider bins were used to reduce the already high computational cost [8]. The

[1] In the present work only one random seed has been used in order to demonstrate the method. In the full analysis at least six will be used to ensure unbiased results are obtained, as defined in IEC 61400-3-2 [8].

binning structure and probability calculation are summarised in FIGURE 1.

The number of occurrence of data in each bin is divided by the total number of hourly sea states (8760 for 1 year worth of data). This result corresponds to the relative frequency of data. The probability of occurrence of each sea state is assumed to be equal to its relative frequency.

Given the finite computational resources it was necessary to define a minimum threshold value for the probability of occurrence for which a particular bin was simulated.A lower threshold signifies a higher percentage of the total sea states being calculated but also a higher computational cost. FIGURE 2 shows the total percentage of hours of the year represented in the bins above a specific threshold over the said threshold.

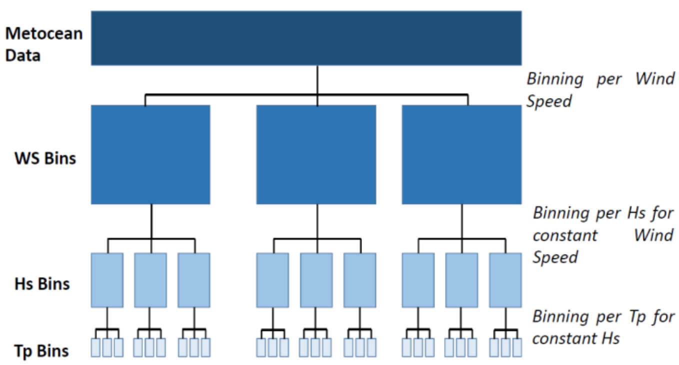

FIGURE 1: METOCEAN DATA BINNING PROCESS

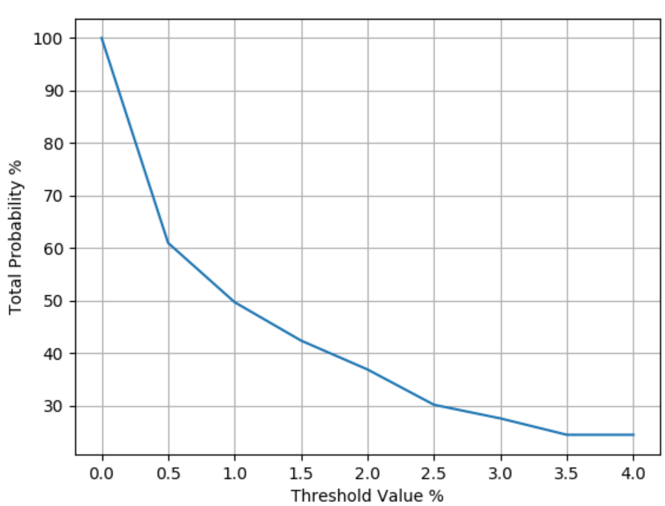

FIGURE 2: BIN PROBABILITY THRESHOLD AGAINST PERCENTAGE OF TOTAL HOURS PER YEAR

3. METHODOLOGY

3.1 Fitting of Spectra

Calculated spectra are derived from the ANEMOC3 hindcast database [12] for every hourly sea state for the whole analysis. For each of these 'Empirical spectra', a spectrum with pre-described mathematical formula is calculated and fitted to the data. This 'Fitted spectrum', is either a JONSWAP or a Bi-modal JONSWAP spectrum, depending on the number of peaks of the Empirical Spectrum. The Bi-modal JONSWAP spectrum is derived by fitting a JONSWAP spectrum, as described in Eq. 2, to each of the two major peaks and then optimising the fit of the sum of these two spectra. Finally, for each group (bin) of sea states, a JONSWAP spectrum is fitted with its Hs and Tp being the bin estimated values and its Peak Enhancement Factor (Gamma parameter) being set to 3.3, that is the experimental value of the "classic" JONSWAP spectrum. This value was also substituted with the recommended value in DNV-RP-C205[11] for the calculation of the accumulated fatigue, leading to 2 subcases for the 'Generalised Bin' case.

The loads estimated by these 4 approaches are processed by a rainflow counting method. The stress ranges and cycles are used to calculate the accumulated fatigue using an S-N curve and Palmgren-Miner's rule.

The integral of each spectral shape, called the zeroth moment of the frequency spectrum, is linked to the significant wave height by the formula:

$$H_s = 4.0 \cdot \sqrt{m_0} \tag{1}$$

The fitting method needs to respect both this criterion as well as the overall goodness of fit. For this reason, two methods were tested:

- A forced fit for exact equal zeroth moment of the curve, which led to higher RMSE between measured and fitted spectral densities and poorer fits as shown in Figure 3.
- An approach of minimising the RMSE of the fitted spectral densities, which yielded higher quality fits, the calculated Hs error was not higher than the bin width (1.0 m) for any case. (see FIGURE 4)

The second method was chosen, due to its better fit around peaks. The fitting process calculates the optimum Peak Enhancement Factor gamma values for the given Hs and Tp and follows an error minimizing process for fitting the JONSWAP formula:

$$S(f) = \frac{5A_\gamma}{16} H_S^2 \omega_p^4 \omega^{-5} e^{-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}} \gamma^a \tag{2}$$

where

H_s is the significant wave height

ω is the angular frequency

ω_p is the peak angular frequency γ is the Peak Enhancement Factor and

A_γ is the normalisation factor (see Eq. (5))

$$a = \exp[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}] \quad (3)$$

$$\sigma = \{\begin{matrix}\sigma_1\ for\ f \leq f_m \\ \sigma_2\ for\ f > f_m\end{matrix} . \quad (4)$$

And $$A_\gamma = 1 - 0.287\ln(\gamma) \quad (5)$$

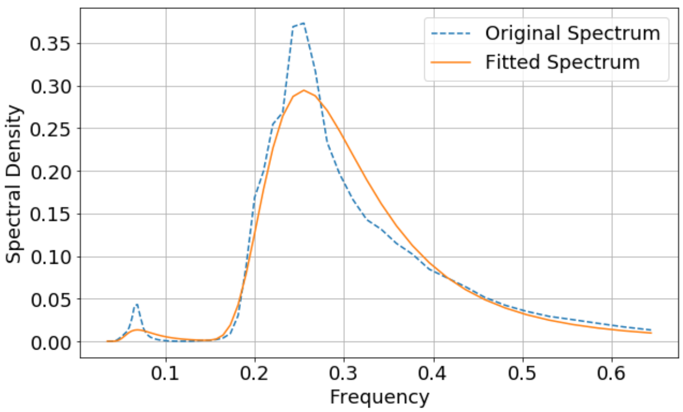

Figure 3: SPECTRUM FITTING THE MINIMISATION OF THE ZERO MOMENT OF THE AREA CRITERION

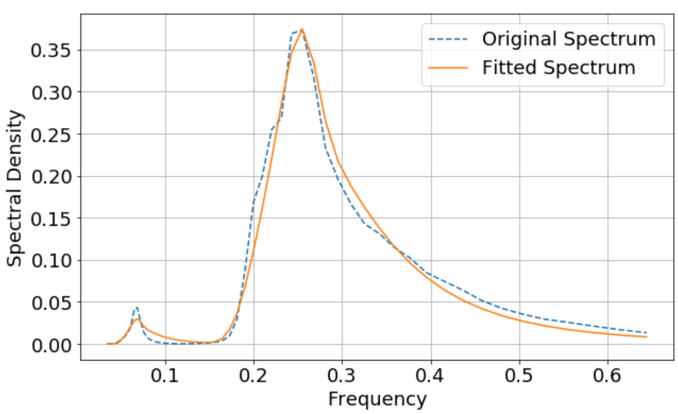

FIGURE 4: SPECTRUM FITTING THE MINIMISATION OF THE RMSE OF THE SPECTRAL DENSITIES VALUES CRITERION

The values for σ1 and σ2 are usually set as 0.07 and 0.09 respectively from empirical studies, but in our study they were optimised along with the gamma parameters. In the case of a bi-modal spectrum, two JONSWAP spectra are fitted to each major peak and their parameters are optimised for the lowest RMSE of spectral densities of the total bimodal fit. This process is repeated for every hourly sea state included in the bins with a probability of occurrence above the selected threshold. In addition, the 'General bin spectrum' is fitted to each bin's Hs and Tp values assuming either gamma=3.3 or gamma values proposed by the DNV-RP-C205[11].

3.2 Simulation Pre-processing

The Environmental Data, when calculated, are used as input to the EDF developed aero-servo-hydro elastic solver DIEGO for the respective number of hourly runs. Wind speed (WS) is considered to be steady and uniform per hourly sea state, while wind and wave directions are assumed identical. The spectral shape values are extrapolated to a 150 frequency and spectral density sample. Using the calculated (WS,Hs,Tp) parameters and Spectral shape, the direction of 0 degrees is chosen, as this direction is aligned with the floater symmetry axis and in-line with one of the mooring lines, as shown in FIGURE 5.

A time-step of 0.1 seconds is used. The model of the IEA 15MW open source turbine mounted on the VolturnUS semi-submersible platform has been created in DIEGO, and the non-linear effects are calculated using the QTF table method, as is also proposed in the Definition of the UMaine VolturnUS-S Reference Platform definition document [14].

The model has been validated and presented in ISOPE2023 (33rd International Ocean and Polar Engineering Conference) [15] .For this study, the total number of runs amount to approximately 8600 hourly simulations, making it necessary for the completion of this study to make use of a source of higher computational capacity. This was offered by the computational cluster 'Cronos' of EDF, where batches of 2500 simulations were launched in parallel. Bending moment values were extracted per every 2nd time step (for reduction of computational cost) and were combined with the compressive stress due to the turbine weight to give the total stress.

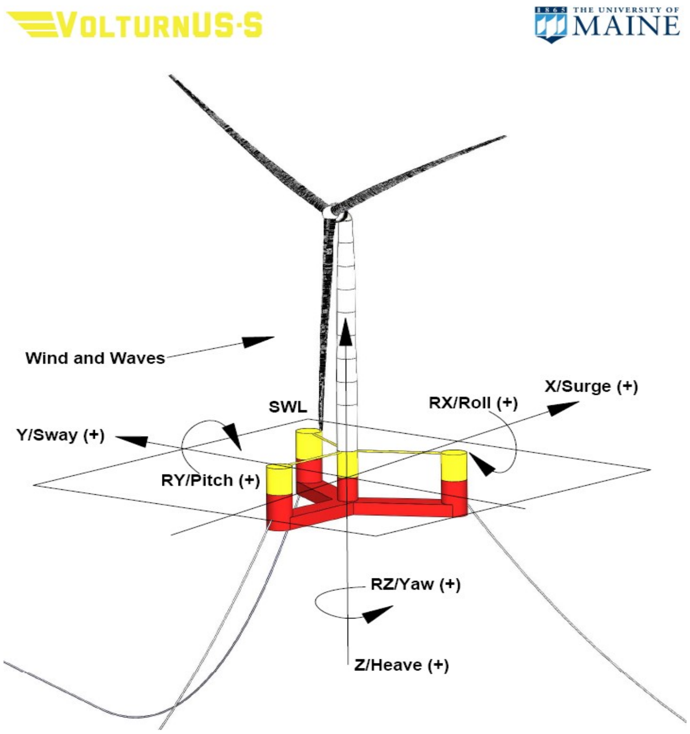

FIGURE 5: THE VOLTURNUS FLOATER AND THE DEFINITION OF DIFFERENT AXIS

3.3 Simulation Post Processing

A total of 61 different bins were studied over the year resulting in 58.37% of the total hours being represented. For each hourly sea state, 4200 seconds were simulated and the first 600 seconds discarded to account for transient effects. The values are represented by the center of each bin.

The resulting bending moments on the X and Y axis, named Mx and My respectively, were combined to calculate the total moment of bending according to the equation:

$$M_{Bend} = M_x \cos(\theta) + M_y \sin(\theta) \tag{6}$$

where θ is the angle of the point of calculation of the loads respective to the x axis. θ was discretised over 30° and was studied in 6 directions, namely from 0 to 150 degrees, due to the symmetry of the floater.

The dynamic vertical forces were neglected due to the static weight being dominant in the z direction, resulting in the total stress calculation as:

$$\sigma = \frac{W}{A} + \frac{M_x c}{I} cos(\theta) + \frac{M_y c}{I} \sin(\theta) \tag{7}$$

where σ is the total studied stress, A the surface of the tower bottom , given by

$$A = \frac{\pi}{4}(D^2 - d^2) \tag{8}$$

with D and d being the outer and inner diameter respectively, I is the second moment of inertia of the surface, given by

$$I = \frac{\pi}{64}(D^4 - d^4) \tag{9}$$

and c is the distance from the tower's neutral axis.

The stresses, and subsequently fatigue, were calculated in the middle of the tower base as is presented in FIGURE 6, where:

$$c = r + \frac{R-r}{2} \tag{10}$$

The stress time-series is processed with the well documented Rainflow counting method, to calculate the stress range and cycles [16]. Then, an S-N curve is chosen from the DNV-RP-C203 [7]. Given that the tower base is 15 m above Mean Sea Level (MSL), and being consistent with past studies on tower fatigue (for example see [2]), a curve of categories 'Air' class D is chosen, presented in FIGURE 7.

Using the Miner Sum the accumulated fatigue is calculated for one year, and this result is multiplied by 25 to get an estimation of the total project life-time fatigue.

To verify the result reliability, the 'General Bin Spectrum' approach was repeated with a lower Hs bin width of 0.5m, while using both the middle or the right edge point of each bin. The four variations of this approach are compared in the Results Section.

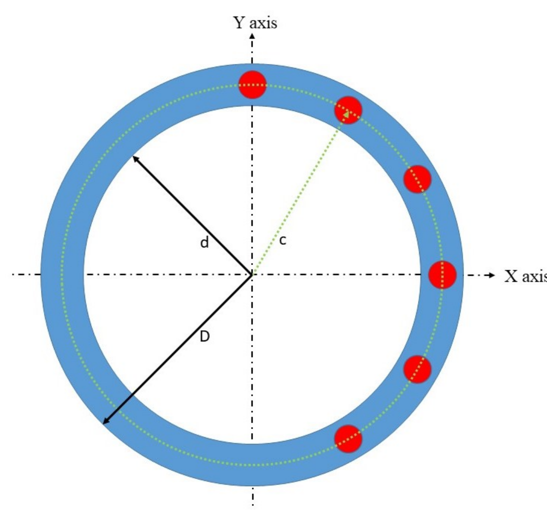

FIGURE 6: FATIGUE ANALYSIS POINTS OF THE TOWER BASE CROSS-SECTION

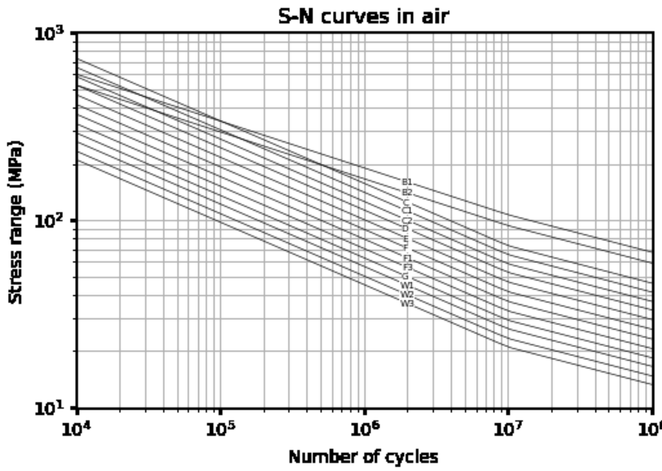

FIGURE 7: S-N CURVES FOR CATEGORY 'AIR' AND VARIOUS CLASSES FROM DNV-RP-C203 [6]

4. RESULTS

For the methods of 'Empirical' and 'Fitted' spectra, the bending moments are calculated for every hourly sea state. For the methods of 'Generalised Bin' spectra, the bending moment is calculated for one hourly sea state with the corresponding bin conditions, and the number of cycles of the respective stress are calculated by the probability of occurrence of the bin multiplied by 8760 (hours/year).

The fatigue results are presented in FIGURE 8, with the highest accumulation of fatigue being on the X/Surge axis. The reason for this directionality is the higher bending moment ranges on the Y axis, leading to higher tensile and compressive loads on the X axis (see FIGURE 6). It is worth mentioning that fatigue is dependent on the time series itself, since the rainflow method measures loading cycles and stress ranges and not just absolute values of loads.

We can also observe that the accumulated fatigue decreases for decrease in the magnitude of angle θ, since the cos term of Eq. 5 decreases and its sin term increases. The use of the Generalised Bin method leads, thus, to the lowest estimations of fatigue, while the Fitted method to the highest, with the Empirical one being between the two. It can also be observed that the use of the DNV-RP-C205[11] recommended peak enhancement (gamma) values returns results slightly different to the use of a constant mean value of 3.3 for the gamma parameter, with relative difference to the Empirical and Fitted methods varying depending on the direction.

The relative error between the four methods, namely the 'Empirical', the 'Fitted' and the 'Generalised Bin' (with its two sub-cases) spectra application methods is presented in FIGURE 9. A relative error of approximately 5.4% is observed between the Empirical and Fitted spectra methods for the 90 degree direction, with the latter giving higher fatigue estimations. This error increases up to 140% for the 0 degrees direction. On the contrary, a relative error of approximately 43% is observed between the 'Empirical' and 'Generalised Bin' method for the 90 degree direction when gamma is set to 3.3. This relative error reduces to 40% when the DNV-RP-C205[11] recommended values are used, with the latter having lower estimations.

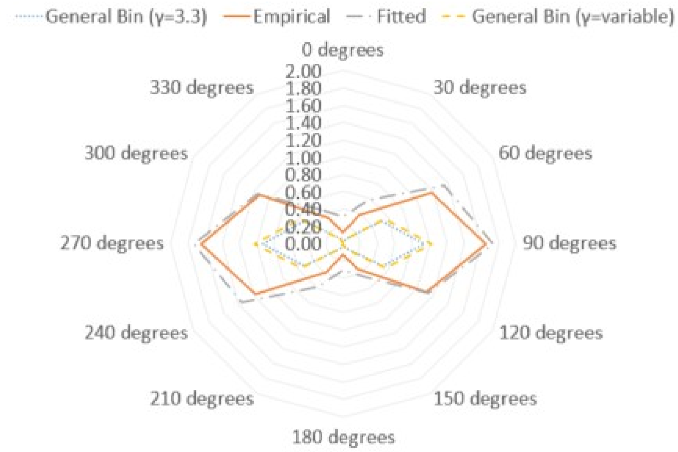

FIGURE 8: ACCUMULATED FATIGUE RESULTS FOR THE FOUR SPECTRA METHODS

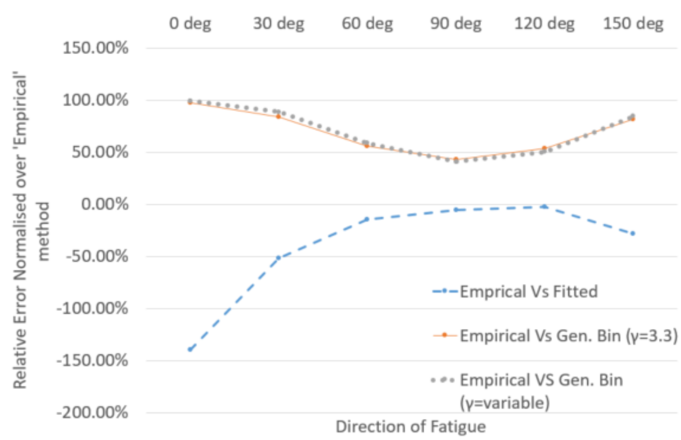

FIGURE 9: RELATIVE ERROR OF ACCUMULATED FATIGUE BETWEEN THE THREE SPECTRA METHODS AND THE EMPIRICAL METHOD

Finally, the 'Generalised Bin' spectrum method was further investigated using a different bin width for Hs (0.5m instead of 1.0m) while ensuring the same number of hours per year are included in the bins. To achieve the same total probability, a lower probability threshold was used since the data were dispersed in a higher number of groups with lower probability due to the lower width.

The lower bin width calculation was repeated with the bins being represented either by the middle point of the bin or the right edge of the bin. The results on accumulated for the different representative points were identical, while the relative error of the lower bin width over the larger bin width fatigue for different angles θ is presented in FIGURE 10.

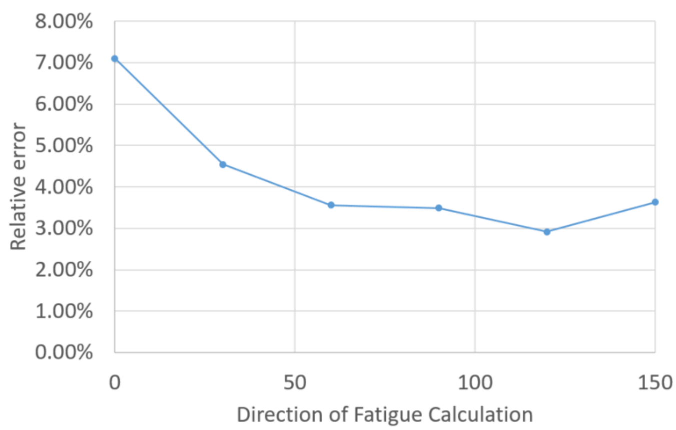

FIGURE 10: RELATIVE ERROR OF ACCUMULATED FATIGUE VALUES OF GENERALISED BIN SPECTRUM METHOD FOR DIFFERENT BIN SIZES

It can be observed in FIGURE 10 that a relative error of up to 7.0% is calculated for the different bin size. The bin size needs to be studied, thus, in future work both for H_s but also T_p and Wind speed bins to quantify its influence on the relative error between the 'Generalised Bin' method and the other two methods.

5. CONCLUSIONS AND FUTURE WORK

The comparison of the four methods suggests a difference in fatigue estimation. The four methods compared were namely:

- The use or not of spectra derived directly from the site conditions instead of pre-described mathematically and then fitted to the specific site conditions.
- The calculation spectra per hourly sea state against the use of a single spectrum for each bin of metocean conditions, using different estimations for the JONSWAP peak enhancement factor value.

The results suggest there is a base for further investigation of this influence to other structural components and using more detailed analysis to quantify the influence of Spectral shape assumptions to fatigue calculations .

The use of different representative points per bin did not seem to influence the calculations. Instead, the bin size did influence the result, suggesting the need of a further sensitivity analysis of the influence of bin size.

Finally, the use of the average Peak Enhancement Factor Gamma value of 3.3 against the recommended values from the DNV-RP-C205 seemed to highly influence the results. In future work, the dependence of the Peak Enhancement Factor gamma to other wave variables (e.g. the significant wave height Hs), and the optimised gamma value will be studied to calculate more accurate formulas for the estimation of this parameter for fatigue calculations.

Finally, future work will include the study of other spectral shapes proposed in DNV-RP-C205 apart from JONSWAP.

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