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The Effect of Marine Growth dynamics in Offshore Wind Turbine Support Structures

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ABSTRACT: Offshore wind turbine (OWT) support structures are invariably subject to colonisation by marine organisms. Marine growth is by no means spatially or temporally linear. It may vary based on location and season, and with structural characteristics such as materials, surface roughness and spatial orientation. Marine growth is a major consideration for engineers. As organisms settle on the structure they may increase surface roughness and cross-sectional area, altering drag and inertia coefficients and increasing hydrodynamic loading. It can be assumed that variability in marine growth would lead to fluctuations in corresponding loading and inertia. Furthermore, the added mass from marine growth also influences structural integrity (i.e. buckling and natural frequency). As such there is considerable uncertainty surrounding the long-term dynamic response of OWTs to marine growth, as this phenomenon is often overlooked in FEA modelling. Parametric FEA modelling is a powerful design tool often used in offshore wind. It is so effective because key design parameters (KDPs) can be modified directly in the code, to assess their effect in the structure's integrity, saving time and computational resources. This paper uses a parametric FEA model of an OWT support structure to analyse how marine growth affects the structural integrity of the system. ULS, FLS, buckling and natural frequencies are investigated against different growth rates and patterns of zonation.

1 INTRODUCTION

Offshore wind turbine (OWT) capacity has grown by 41.1% from 2010 to 2015 [1]. The deployment of 4-6 MW turbines seen in 2015 will be followed by the gradual introduction of 6-8 MW turbines closer towards 2018 [2]. In fact, The North West of the UK is home to the world's largest OWT with a capacity of 8 MW each, which are currently under construction. The rapid growth in capacity and size, presents some issues to the scale-up of OWTs due to the dynamic sensitivity of the structures. Furthermore, OWT support structures are invariably subject to colonisation by marine organisms, which are believed to have an impact on OWTs structural integrity.

Marine growth refers to the colonisation of submerged structures by marine organisms with sessile life stages, referred to as epibenthic organisms, and is a major challenge for engineers. As organisms settle on the structure they may increase surface roughness and cross-sectional area, altering drag and inertia coefficients and increasing hydrodynamic loading. It can be assumed that variability in marine growth would lead to fluctuations in corresponding loading and inertia. Furthermore, the added mass from marine growth also influences structural integrity (i.e. buckling and natural frequency). As such there is considerable uncertainty surrounding the long-term dynamic response of OWTs to marine growth, as this phenomenon is often overlooked in FEA modelling. Parametric FEA modelling is a powerful design tool often used in offshore wind. It is so effective because key design parameters (KDPs) can be modified directly in the code, to assess their effect in the structure's integrity, saving time and computational resources.

This paper uses the parametric FEA model of an OWT support structure developed in [3] to analyze how critical the marine growth effect is in the structural integrity of OWT support structures. A review of how the Oil and Gas Industry has approached this issue in the past and how the Offshore Wind Industry can benefit from their knowledge is presented in Section 2. Section 3 shows a summary of the baseline turbine and parametric FEA model, along with the loading conditions presented in Section 4. ULS, FLS, buckling and natural frequencies are investigated against different growth rates and patterns of zonation and presented in Section 5. Finally, results and conclusions can be found in Section 6 and 7.

2 MARINE GROWTH

Settlement of epibenthic organisms is determined and influenced by multiple factors including season, species presence, life cycle and life stage requirements, prevailing environmental conditions, and features and characteristics of the substrate.

Seasonal variation in settlement is evident from a number of studies [3, 4]. In the North Sea biomass has been shown to peak in the summer, with lowest levels observed in the winter and spring [4]. This is supported by [3], who reported that species richness increased from February to July, with densities increasing 10-20 fold, in the southern North Sea. In addition, surveys of a Belgian offshore wind farm in 2008 and 2011 have demonstrated seasonal variability in epibenthic coverage. Down to a depth of -2 m Mytilus edulis coverage varied from 0-60% in February, but increased to 90-100% in September [6].

Early research on colonisation stemmed from the observation that, on rocky shores, organisms occupied distinct bands both above the waterline and below. It is now well known that this pattern of zonation is a result of localized environmental characteristics forming small scale habitats resulting to varying levels environmental parameters, such as nutrient transport, current regimes or wave exposure. Indeed exposure to wave action can influence the distribution and morphology of epibenthic organisms. Shell lengths in dogwhelks, Nucella lapillus, have been found to be shorter and wider on exposed shores whilst having elongated, narrower spires at sheltered locations [7]. Wave exposure has also been shown to effect growth rates in epibenthic invertebrates. Waves and water flow influence light levels, oxygen and sediment movement and nutrient availability [8]. Maximum growth rates have been found in areas with intermediate levels of exposure, with highly exposed and highly sheltered locations showing a sharp reduction in growth rates [9]. Indeed impact of waves place hydrodynamic forces on epibenthic invertebrates, such as mussels, and may cause them to become damaged or dislodged [9, 13]. Therefore settlement and post settlement survival may be reduced in areas of heavy wave action.

Similar patterns have been found on offshore structures. Zonation in relation to depth has been described in communities colonising offshore oil and gas platforms as well as wind turbine substructures [6]. Southgate and Myers [12] found that, for the Celtic Sea Kinsale Field gas platform, mussels of Mytilus spp formed the dominant colonising organism between 6 and 20 m. Whilst, between -20 m and -30 m the soft coral, Alcyonium digitatum, and anemone, Metridium senile, dominate. At depths below -30 m Serpulid worms are the dominant organisms. In the case of the Montrose Alpha North Sea oil platform mussels were absent and down to -10 m epibenthic communities were dominated by macro algae, with arborescent bryozoa and hydroids [13]. However below -10 m macro algae gave way to arborescent bryozoa and hydroids and below -30 m hydroids, calcareous and encrusting bryozoa dominated [13].

The effects of wave action on growth rates and post settlement mortality or dislodgement of epibenthic organisms has received less attention in relation to offshore structures than on rocky shores. However, it is likely that areas of structures exposed to wave action would also show variation in marine growth over time and between seasons, as winter storms would increase wave action. It is also likely that variation in growth would be seen between sheltered and exposed areas of structures.

Marine growth can increase surface complexity and roughness on marine substructures, which provides new habitat and secondary substrate for colonisation. For example, mussels have been found to provide secondary hard substrate and shelter for other epibenthic species on oil and gas platforms as well as wind turbine monopiles [8, 5].

Surface complexity, orientation and roughness are known to be important for settlement of invertebrates [9, 10, 11, 12]. On spatial scales of µm to cm, substratum topography or quality can affect survival after settlement of barnacles, hydrozoans and bryozoans [19]. Rough surfaces may increase survival rates as pits and crevices provide refuge from predators and physical disturbance. This was noted by Walters and Whethey [19] who found that in species with limited attachment ability post settlement survival was greatly increase on plates with rough surfaces.

Although marine growth is an important consideration in the design and operation of offshore structures, the dynamic response of epibenthic communities has not been fully realized by engineers. Indeed, it has been stated in recommended standards that marine growth ‘tapers off after a few years’ [20]. Whilst there is evidence supporting the idea of succession following a predictable pattern [21] it is expected that even an ecosystem with a mature community will experience cyclical change. Thick layers of growth can become dislodged, particularly by storms in the winter period, creating patches of new substrate for colonisation [6]. Furthermore, artificial structures present habitat for invasive species. In the North Sea and Baltic Sea invasive species have been recorded on offshore wind turbine substructures in [22]. It is possible that competition between introduced and indigenous species could result in changes to the surface profile of structures.

3 PARAMETRIC FEA MODELLING OF OWT SUPPORT STRUCTURES

3.1 Geometry

The reference site is located off the coast of North Wales. The reference turbine used for this analysis consists of a 3.6MW Siemens turbine, connected to an 80m tower, a transition piece (TP) and is sustained by a monopile (MP) foundation. The MP is 31m long and is embedded 18m into the soil and submerged 11m into the ocean. The TP is 24m in length and joins together the MP and the tower. Six stoppers located in the internal surface of the TP, would allow it to rest on top of the MP. The GC, located between the TP and the MP, is used for the appropriate transmission of loads and stresses. The OWT support structure was modelled using Abaqus, which is a widely used FEA software.

3.2 Materials

MP, TP, and tower are made of steel S355 with a density of 7850 kg/m3, a Young's modulus of 210 GPa, a Poisson's ratio of 0.3 and a nominal yield strength of 355 MPa. The GC's material properties are characterised by a density of 2740 kg/m3, a Young's modulus of 88 GPa, a Poisson's ratio of 0.19 and friction coefficient of 0.6 [23]. Furthermore, a material factor of 1.35 was used.

Apart from the OWT support structure, an important part of the detailed parametric model is composed by the soil-structure interaction. The soil profile considered in this analysis consists of one layer of sand and 3 layers of clay. Composition of soil profiles strongly depends on the geographical emplacement; the soil profile utilised in this analysis corresponds to the North of the UK. Winkler's approach was used to represent the soil profile. This method is widely used to model the soil-structure interaction by replacing the elastic soil medium by closely spaced and independent elastic springs [24,25]. Furthermore, it is the recommended by DNV-GL [26], where the stiffness of the linear springs used in the Winkler's approach, is calculated from the p-y curves [27]. This method is used for the design of horizontal loaded piles by the American Petroleum Institute (API) code [28], and it calculates the lateral soil resistance (p) as a function of lateral soil displacement (y).

3.3 Mesh

A mesh sensitivity analysis was performed in order keep a balance between the computational time of the simulations and the accuracy of the results. After the analysis, a mesh size of 0.1m was found to be adequately accurate as results had already converged.

3.4 Validation

This model was validated by comparing the results of the modal analysis of both the structure and the tower, against data from the reference OWT. These results can be found in [3].

4 LOADING CONDITIONS

4.1 Wind

For representation of wind climate, a distinction is made between normal and extreme wind conditions. The former generally concern cyclic structural loading conditions, which are important for fatigue assessment, while the latter are wind conditions that can lead to extreme loads, which might lead to the collapse of the structure due to excessive loading [29]. Both normal and extreme wind conditions used in this analysis were calculated in accordance with IEC 61400-1 [30].

4.2 Wave

Wave loading is another environmental load that influences the structural integrity of OWT support structures. Wave forces are calculated using Morrison's Equation [31], which is characterised by the inertia and drag terms, composed by their coefficients (C_m and C_D respectively). Morrison's Equation can be expressed as:

$$dF_t = dF_M + dF_D = C_M \rho \pi \frac{D^2}{4} \ddot{x} dz + C_D \rho \frac{D^2}{2} |\dot{x}| \dot{x} dz$$

where $\dot{x}$ represents the undisturbed fluid velocity, $\ddot{x}$ the acceleration of the fluid (calculated for the baseline turbine in [3]), ρ the water's density and D the effective diameter (including marine growth). According to [20], most of the variation in C_D and C_M due to marine growth is produced by variations in: relative surface roughness (e = k/D), Reynolds number ($Re = \rho \dot{x} D / \upsilon$), Keulegan-Carpenter number ($KC = \dot{x} T / D$), and the member orientation. Being υ the kinematic viscosity of water, T the period of oscillation and k is the absolute roughness height.

Mass and drag coefficients, C_M and C_D, are usually estimated according to the offshore standards [26] and [20] by firstly, deriving the drag coefficient for steady-state flow (C_{DS}) and the wake amplification factor ($\psi(K_c/C_{DS})$), which depends on KC and C_{DS}.

There is a high dependence of C_{DS} on relative surface roughness, as shown in [20]. Natural marine growth on platforms will generally have e > 10^{-3}. The marine growth used in these case studies is in the range from 0.015< e >0.002. CM and CD coefficients were calculated from the tables present in [20], for each one of the different marine growth cases.

4.3 Tidal and current induced loads

Tidal currents and wind driven currents are two environmental loads in which marine growth can have an impact and vice versa. Even though they do not represent major hazards to the structure's integrity in shallow waters, they contribute to other major excitations such as those produced by the wind and waves. The tidal current profile can be represented as the current speed $(v\ (z))$ at distance z, from still water level (positive upwards), which is the exponential variation of the current at still water level v_0 through the distance to the top of the water column z.

4.4 Hydrostatic Pressure

Hydrostatic pressure is referred to the pressure of the water column applied to the submerged parts of the MP and TP. It can be calculated from a control volume analysis of an infinitesimally small cube of fluid and simplified as density and gravity are constant through depth as in [3].

4.5 *Nacelle's and Rotor's Weight*

Since the nacelle's and rotor's (composed of the hub and blades) detailed modelling is not part of the parametric model, they are included in the FEA as concentrated or distributed masses in order to be able to reproduce accurately the OWT's structural behaviour. According to [32], there is no need to model the blades due to the fact that, aside from the mass added to the tower top, parked and feathered blades have minimal impact on the natural frequency of OWTs. The nacelle's and rotor's weights are 125 and 95 tons respectively, which makes a total of 220 tons that are accounted as a cylinder three metres high and with the same diameter as the top of the tower. The density was increased accordingly in order to account for the total weight. The nacelle's and rotor's weights were found in the official Siemens SWT-107 3.6 MW brochure [33].

5 EFFECT OF MARINE GROWTH IN OFFSHORE WIND TURBINE SUPPORT STRUCTURES

5.1 Limit States Formulation

Structural integrity of the system is checked according to DNV-OS-J101 [26]. According to this standard, four limit states have to be considered in the design: ULS, FLS, Accidental Limit State (ALS) and Serviceability Limit State (SLS). Modifications in the design are checked upon ULS and FLS. ALS was not considered as this limit state is used for the assessment of structural damage in the structure, caused by accidental loads or to re-assess the ultimate resistance and structural integrity after damage. Similarly, SLS was not taken into account as it considers tolerance criteria applicable to normal use of the OWT support structures. Furthermore, the structural performance of the system was also checked upon buckling and natural frequencies.

5.1.1 ULS:

ULS analysis is carried out considering extreme environmental conditions the worst case scenario for a 50 year return period. This is when wind, wave, tides and wind driven currents are aligned in the principal direction of the wind. The load factor to be used when different loads are combined to form the design load is 1.35 [26].

Table 1 shows the Maximum Utilisation Rates (MUR) for the MP the baseline case, which will be use to assess the loss or gain of the structural integrity of the different design cases considered.

5.1.2 FLS

FLS refers to the cumulative damage in the structure due to cyclic loads. The fatigue design of OWT support structures is governed by dynamic responses from simultaneous aerodynamic and hydrodynamic loads [34]. The load factor in the FLS is 1.0 for all load categories [26]. Normal sea state conditions (significant wave height and peak spectral period) were used for the calculation of wave loading [35]. Wind loads were taken from [36], where the fatigue thrust load for the tower of a 3.6 MW offshore wind turbine with 100m hub height are 143 kN.

S–N curve approach is the recommended by the standards [26] and [35]. Furthermore, the equivalent stress range (ΔS) can be determined from the parametric FEA model subjected to the before mentioned fatigue loads. Having obtained the equivalent stress range, the number of loading cycles to crack initiation, in Equation 15, can then be determined from the S – N curve.

The selection of the S – N curve plays a massive role in the results obtained. Offshore structures are prone to corrosion development due to the harsh marine environment, which leads to significant levels of damage to the structures and hence a reduction in service life [37]. For that reason, curve D in seawater with adequate cathodic protection is used in service life calculations [38]. Table 1 shows the stress range ΔS and the expected service life in the baseline turbine.

5.1.3 Buckling

Buckling is characterised by the sudden failure of a structural member subjected to high compressive stress, when this is, at the point of failure, less than the ultimate compressive stress of the material. When the applied load is increased on a slender structure, such as a WT, there is the possibility that it becomes large enough to cause the structure to lose its stability and buckle.

Eigenvalue linear buckling analysis is generally used to estimate the critical buckling load of the analysed structure. The buckling loads are calculated relative to the base state of the structure. The buckling stability of shell structures is often checked according to DNV-RP-C202 [39] or Eurocode 3/ EN 1993-1-1 [40] and Eurocode 3/ EN 1993-1-6 [41]. In this analysis Abaqus CAE is used to assess it. Table 1 shows the buckling frequency in the baseline turbine.

5.1.4 Natural frequencies

A classic aspect of good structural design lies in optimizing stiffness-to-mass ratio through material and shape choices. Natural frequencies' sensitivity analysis were carried out for the different case studies with the aim to detect patterns of change in the characteristic natural frequencies of the structure. Table 1 shows the first 5 eigenfrequencies of the baseline turbine.

Table 1. Structural properties of the baseline OWT

ULS	MUR (%)	
	MP	64.73
FLS	ΔS (MPa)	Fatigue life (yr)
	33.9	33.1
Buckling Frequency		
	1.5316 Hz	
Natural Frequency		
Mode 1	0.2909 Hz	
Mode 2	0.2962 Hz	
Mode 3	1.6776 Hz	
Mode 4	1.7211 Hz	
Mode 5	1.9516 Hz	

5.2 Case Study 1: Effects of Zonation

This section analyses the impact that two different marine growth profiles have in the structure's integrity and modal frequencies. As pointed out in previous sections, marine growth profiles can substantially vary depending on a number of factors. For this case study, two different profiles were developed based on existing data from the North Sea and Irish Sea were chosen [6,12]. The submerged part of the structure is 11m. Three different zones and the types of marine growth for each of the two profiles are presented in Figure 1. In these cases, the thickness on the exposed part of the structure were assumed to be smaller based on dislodgement through hydrodynamic pressure. However, this assumption may not always hold true in nature.

Figure 1

Table 2 shows the material properties for each of the zones of the two profiles. In order to introduce marine growth in the parametric FEA model, two half, hollow, circular cylinders are made for each zone, to surround the MP. One of these was positioned in the side of the MP exposed to currents and waves and its thickness is denoted as Ex. Thickness and the other half was positioned in the sheltered side and therefore is denoted as Sh. Thickness.

Relevant material properties of the different species, like bulk density (ρ), thickness, Young's Modulus (E) and Poisson's ratio (υ), have been carefully taken from relevant literature [37, 38].

Table 2. Profile's material properties of the baseline OWT

Profile & Zone	ρ (g/cm^3)	Thickness (cm) Ex.	Thickness (cm) Sh.	E (GPa)	υ -
A I	3.1	17.5	4.4	0.85	0.5 [43]
A II	0.7* [44]	17.5	4.4	1.27* [44]	0.3 [42]
A III	0.6 † [44]	3.0	0.8	1.13† [44]	0.3 [42]
B I	3.1	20.0	5.0	0.85	0.5 [43]
B II	3.1	12.5	3.1	0.85	0.5 [43]
B III	0.6† [44]	12.5	3.1	1.13† [44]	0.3 [42]

* Values correspond to the average value plus the standard deviation.
† Values correspond to the average value minus the standard deviation

5.3 Case Study 2: Effects of Thickness

In this section a sensitivity analysis of the marine growth thickness, both at the exposed and the sheltered parts of the MP, of the two profiles presented in the previous section, was developed. The mean value of the range of thicknesses at different depths presented at Figure 1, was the one used in the previous Case Study. Case Study 2 analyses the effect that these ranges of thickness have in the structural integrity of the unit. Table 3 presents the different cases that compose the sensitivity analysis.

Table 3. Thickness' Sensitivity analysis

Profile & Zone		Case 2 Sh.	Case 2 Ex.	Case 1 Sh.	Case 1 Ex.	Baseline Sh.	Baseline Ex.	Case 4 Sh.	Case 4 Ex.	Case 5 Sh.	Case 5 Ex.
	I	5.0	1.3	11.3	2.8	17.5	4.4	23.8	5.9	30.0	7.5
A	II	5.0	1.3	11.3	2.8	17.5	4.4	23.8	5.9	30.0	7.5
	III	1.0	0.3	2.0	0.5	3.0	0.8	4.0	1.0	5.0	1.3
	I	10.0	2.5	15.0	3.8	20.0	5.0	25.0	6.3	30.0	7.5
B	II	5.0	1.3	8.8	2.2	12.5	3.1	16.3	4.1	20.0	5.0
	III	5.0	1.3	8.8	2.2	12.5	3.1	16.3	4.1	20.0	5.0

6 RESULTS & DISCUSSION

6.1 Case Study 1: Effects of Zonation

Two different marine growth profiles typical from the North and Irish Sea were implemented in the parametric FEA model to analyse the impact that predominant species would have in the structural integrity and natural frequencies of the unit. This impact is mainly caused by the added mass of the marine growth and the how these species change the roughness of the structure and therefore its dynamic coefficients (C_M and C_D). Average values of marine growth for Profile A and B were used to compare the structural integrity and modal frequencies of the unit to the case where no marine growth exists (Table 4).

Table 4. Effect of zonation results: structural properties.

Profile & Zone	Profile A	No Marine Growth	Profile B
ULS			
MUR (%)	68.3	68.3	68.3
FLS			
ΔS (MPa)	40.4	33.9	40.5
F. Life (yr)	13.7	33.1	13.5
Buckling Freq. (Hz)	1.532	1.532	1.532
Natural Freq. (Hz)			
Md. 1	0.2913	0.2909	0.2911
Md. 2	0.2961	0.2962	0.2959
Md. 3	1.6647	1.6776	1.6587
Md. 4	1.7051	1.7211	1.6994
Md. 5	1.9547	1.9516	1.9547

Results presented in Table 4 show no significant variation either in the unit's MUR % or buckling frequency, for both marine growth profiles in comparison to no marine growth development. The reason why these two structural checks show no variation due to marine growth might be due to the fact that extreme wave loading is not affected by marine growth. This is because extreme waves hit the turbine's support structure in a region well above the mean water level and splash zone, where marine growth does not develop. Therefore, dynamic coefficients are not affected and loading conditions are maintained. Hence the lack of variation.

Although the added mass does not have an influence in buckling frequency, the fact that organisms are stuck to the support structure's surface affects the modal frequencies and deflections of the turbine. As could be expected, the presence of these organisms in the surface of the support structure increases its rigidity, increasing natural frequencies. However, the rate of variation of the natural frequencies is not high enough for marine growth to be considered a threat to the structure's integrity. This is due to the low rate of change and also due to restrictions on the growth of epibenthic organisms. Whilst layers of epibenthic growth of up to 300 mm may occur, intense wave action can dislodge thick layers of marine growth. Furthermore, a special degree of variation is observed in Mode three and four, which could potentially be used for Structural Health Monitoring purposes.

Table 4 also shows the impact that marine growth has in the stress range of the unit, at mudline level. Even if this variation is low, the impact that it has in the estimated service life of the structure is great. This is due the logarithmic scale present in the S – N curves. Nevertheless, the level of damage that can be expected due to marine growth is never going to be constant, as it will always depend on the current level of marine growth development, which is highly variable. According to Table 4, Mussel dominated profiles may present a greater threat to the structure than barnacle dominated profiles, showing a variation in expected service life from 33.1 to 13.5 years for Mussel-dominated profiles and from 33.1 to 13.7 years for Barnacle dominated profiles.

6.2 Case Study 2: Effects of Thickness

A sensitivity analysis of the marine growth thickness, both at the exposed and the sheltered parts of the MP, of the two profiles was carried out. The mean value of the range of thicknesses at different depths presented at Figure 1 and used in the previous Case Study constitutes the baseline scenario in this Case Study. This Case Study analyses the effect that these ranges of thickness have in the structural integrity of the unit compared to the baseline scenario of each profile. Table 5 presents the results for each one of the different cases that compose the sensitivity analysis.

Similar to the previous Case Study, there is no variation in the MUR and buckling frequencies in any of the cases of both profiles. This lack of variation is consistent to the results of the previous Case Study, where the effect of zonation was explored. This is because it is unlikely that the added mass from the positive variation in thickness of Cases three and four would impact the structural behaviour, when the transition from the "no marine growth scenario" to the baseline marine growth did not.

Table 5. Sensitivity Analysis' results: structural properties.

Profile	Case 2	Case 1	Baseline	Case 3	Case 4
	ULS	MP's MUR (%)			
A	68.3	68.3	68.3	68.3	68.3
B	68.3	68.3	68.3	68.3	68.3
	FLS	Fatigue life (yr)			
A	14.5	14.4	13.7	13.3	12.7
B	15.9	14.0	13.5	10.2	9.7
	Buckling Frequency (Hz)				
A	1.532	1.532	1.532	1.532	1.532
B	1.532	1.532	1.532	1.532	1.532
	Natural Frequency (Hz)				
A					
Md. 1	0.2912	0.2912	0.2913	0.2913	0.2914
Md. 2	0.2960	0.2960	0.2960	0.2960	0.2960
Md. 3	1.6754	1.6701	1.6647	1.6592	1.6536
Md. 4	1.7154	1.7103	1.7051	1.6998	1.6944
Md. 5	1.9547	1.9547	1.9547	1.9548	1.9549
B					
Md. 1	0.2912	0.2911	0.2911	0.2911	0.2911
Md. 2	0.2960	0.2959	0.2959	0.2959	0.2959
Md. 3	1.6698	1.6642	1.6587	1.6529	1.6472
Md. 4	1.7101	1.7047	1.6994	1.6938	1.6884
Md. 5	1.9547	1.9547	1.9547	1.9547	1.9548

In line with the natural frequency results from the Effect of Zonation study, the rate of variation of the first natural frequency is maintained with the thickness variation and it is still not high enough for marine growth to be considered a threat to the structure's integrity. Besides, Modes three and four stand as the ones where higher variation in the natural frequency is seen. This fact makes them potentially useful to detect excessive marine growth development with Structural Health Monitoring Systems. The detection of excessive marine growth would be beneficial to extend the fatigue life of the structure, as according to Table 5, that constitutes the biggest threat that marine growth presents to OWT support structures.

Fatigue is the structural feature most affected by Marine Growth, according to these analyses. As it can be appreciated from Table 5, Marine Growth has a great impact in the fatigue life of the structure, as a reduction of 58.6-59.2% is presented in the baseline scenarios. This impact is reduced to the 52% for the minimum marine growth development case, although this variation is still very high.

7 CONCLUSSION

This paper used the parametric FEA model of an OWT support structure developed in [3] to analyze the criticality of marine growth in the structural integrity of OWT support structures. To that aim, two marine growth profiles typical from the North and Irish Sea were introduced in the parametric FEA model. Due to this marine growth, dynamic coefficients needed to be recalculated, which also affected the loading conditions. ULS, FLS, buckling and natural frequencies have been investigated against different growth rates and patterns of zonation.

Results show no effect in the maximum utilisation ratios (MURs) and buckling frequencies, which draws the conclusion that the added mass of the marine growth has little or no influence in the system. Furthermore, natural frequencies were also not very affected due to this phenomenon. However, could be expected, the presence of these organisms in the surface of the support structure slightly increases its rigidity, increasing natural frequencies in both profiles but specially in Profile A (barnacle dominated).

Fatigue is the structural feature most affected by Marine Growth, according to these analyses. Marine Growth has a great impact in the fatigue life of the structure, as a reduction of 58.6-59.2% is presented in the baseline scenarios. This impact is reduced to the 52% for the minimum marine growth development case, although this variation is still very high. It is also convenient to bear in mind that marine growth shows considerable variability, therefore the present reduction in fatigue life is likely to be slightly mitigated. In conclusion, awareness should be raised to operators in order to mitigate this phenomena.

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