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Motion sickness predictions for floating wind turbine motion data

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Executive summary

Simulated nacelle acceleration data for floating wind turbines with a semisubmersible and Tension Leg Platform (TLP) floater were used to generate predictions for motion sickness experienced by maintenance engineers inside the nacelle given a range of five different sea states (varying in wave height and wave period). Predictions from the ISO 2631-1 model were compared to those from a new TNO model, which is based on the ISO model but extends it to encompass accelerations along all three cardinal axes and predicts not only emesis but also pre-emesis symptoms. Both models predicted very low levels of motion sickness for 30-minute exposures. The likelihood of motion sickness was predicted to increase with wave height (from 1.5 to 2.5 m), while wave period had a non-linear effect (highest likelihood of motion sickness for 8 s, lower for 6 and 10 s). The TNO model predicted a probability of people inside the nacelle experiencing nausea after 3 hours of exposure of about 5%, with a slightly higher probability for the semisubmersible base than for the TLP base. The probability of emesis was close to zero according to the TNO model and slightly higher according to the ISO model. The results suggest that motion sickness may be a concern in floating wind turbines, suggesting a need for more empirical data to validate existing prediction models for this particular application domain.

Contents

1 Introduction

The rising demand for clean energy is expected to drive the expansion of offshore wind farms, particularly in deep-sea locations where floating foundations will be necessary. These future wind turbines will be taller and larger than those currently in use. While larger turbines do not necessarily experience more motion, their increased size alters the frequency and magnitude of movements. These dynamic effects, combined with exposure to waves and wind, could impact stability in the nacelle. As a result, motion sickness in maintenance engineers working on these floating wind turbines may become a significant concern. As no empirical data on either nacelle motion or motion sickness for this type of wind turbine are available, prediction models may provide insight into the likelihood of motion sickness given a certain sea state and wind condition combined with different types of floating bases. However, the prediction model in the only available international standard on motion sickness, ISO 2631-1[4], is expected to have only limited applicability for this situation. This model was developed specifically to predict seasickness and therefore only takes vertical accelerations into account. Moreover, it only predicts motion sickness incidence (the percentage of the population expected to end up vomiting due to motion exposure) as an outcome variable and therefore cannot predict lower degrees of motion sickness, which still may have debilitating effects on performance. Recently, TNO has developed an extended version of the ISO 2631-1 model, which is based on linear accelerations along all three cardinal axes (longitudinal, lateral and vertical) and predicts various degrees of motion sickness [2]. Moreover, it allows for predictions for groups of people with different motion sickness susceptibility as measured with the Motion Sickness Susceptibility Questionnaire (MSSQ [3]). ORE Catapult has asked TNO to apply TNO's motion sickness prediction model to simulated nacelle acceleration data for two different types of floating bases (semisubmersible and TLP), each with five different sea states. The goal is to compare motion sickness predictions for the two base types and assess the potential influence of sea state for both bases. In addition, the predictions will be compared to those from the ISO 2631-1 model. This report describes the process and the results.

2 Prediction models for motion sickness

2.1 ISO 2631-1 model of motion sickness

According to the ISO 2631-1 standard, motion sickness (operationalised as the motion sickness incidence (MSI) or proportion of people reaching emesis due to motion exposure) is expected to be a linear function of the time integrated frequency weighted accelerations that a person is exposed to [4]. This is termed the Motion Sickness Dose Value (MSDV) and computed according to:

$$MSDV = \left\{\int_0^T [a_w(t)]^2 dt\right\}^{\frac{1}{2}} \tag{1}$$

where $a_w(t)$ represents the frequency weighted vertical acceleration time series and T is the duration of motion exposure (in s). The standard provides a frequency weighting function for motion sickness, which peaks at 0.16 Hz, suggesting that accelerations at this frequency will contribute the most to motion sickness, with both lower and higher frequencies contributing less. Outside the frequency range between 0.1 and 0.5 Hz accelerations are not expected to contribute much to motion sickness. According to ISO 2631-1, the proportion of people expected to end up vomiting can be approximated by:

$$MSI = K_m \cdot MSDV \tag{2}$$

with K_m = 1/3 for a normal unadapted population consisting of 50% males and 50% females. This model was based on extensive lab data concerning vertical acceleration exposure. Although not validated for the prediction of motion sickness due to accelerations in the horizontal plane, MSDVs can be calculated using Equation 1 for all three motion axes separately and then combined in the following way:

$$MSDV_{3DoF} = \left(k_x^2 MSDV_x^2 + k_y^2 MSDV_y^2 + k_z^2 MSDV_z^2\right)^{\frac{1}{2}} \tag{3}$$

Here, we have used this approach to apply the ISO 2631-1 model to nacelle acceleration data. The three axes were assumed to contribute equally to motion sickness by taking $k_x = k_y = k_z = 1$.

2.2 TNO extended 3 DoF model of motion sickness

Based on extensive lab studies (n = 107) on the impact of longitudinal, lateral and vertical accelerations with different frequencies and magnitudes on motion sickness, TNO has developed an extended version of the original ISO 2631-1 model. These studies were done in motion simulators that allowed participants only to see the inside of the simulator cabin.

To measure motion sickness, the Motion Illness Symptoms Classification scale (MISC) was used, which allows participants to indicate the type of symptoms they are experiencing as well as the severity of those symptoms on an 11 point scale (see Figure 1) [1,6]. Participants gave a MISC score every 2 minutes and test sessions were ended when participants gave a MISC score higher than 6 or after 20 minutes.

Symptoms		MISC
No problems		0
Some discomfort, ***but no specific symptoms***		1
Dizziness, cold/warm, headache, stomach/throat awareness, sweating, blurred vision, yawning, burping, tiredness, salivation, ... ***but no nausea***	vague	2
	little	3
	rather	4
	severe	5
Nausea (possibly with other symptoms)	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Figure 1. MISC scale for measuring motion sickness.

Based on the MISC data from these studies, the frequency weighting function as given by ISO 2631-1 was adapted to best fit the data. This new frequency weighting function peaks at a slightly higher frequency (0.23 Hz) than the function from the ISO standard and attributes higher weights to frequencies above 0.2 Hz (up to about 5 Hz). Moreover, the MISC results also suggested that lateral motion contributed less to motion sickness than longitudinal and vertical motion. Therefore, the weighting factors k_x, k_y and k_z in Equation 3 were set to $k_x \approx k_z$ and $k_y < k_z$. The $MSDV_{3DoF}$ values are input to a probability model that predicts the proportion of people expected to give a MISC rating above a certain criterion value c:

$$P(MISC > c) = \Phi(\beta_1 + \beta_2 MSDV_{3DoF}) \qquad (4)$$

where Φ represents the Gaussian cumulative density function, β_1 is a linear function of criterion c and the assumed population susceptibility S and β_2 is also a linear function of S (S is the percentile score based on the Motion Sickness Susceptibillity Questionnaire score [3]). In the simulations presented below, an average susceptibility S = 0.5 was assumed. P(MISC > 0) would represent the proportion of people expected to suffer from any motion sickness symptom, no matter how slight or severe, P(MISC > 5) gives the proportion of people predicted to suffer from nausea in various degrees and P(MISC > 9) indicates the proportion of people expected to vomit (similar to the MSI from ISO 2631-1).

3 Input data

ORE Catapult provided TNO with ten acceleration data sets. Half these sets represented acceleration data simulated for the nacelle of a wind turbine with a floating semisubmersible base, while the other half was for a wind turbine with a TLP. For each base, nacelle accelerations for five different sea states, defined by wave height Hs and period Tp were provided (see Table 1). These states were chosen to test the motion sickness predictions with a range of different acceleration spectra and magnitudes deemed representative of sea conditions during wind turbine maintenance operations. The nacelle acceleration data were computed for exposures up to 30 min, with wind turbines were assumed to be in parked position for the entire duration.

Table 1. Simulated sea state conditions (Hs = wave height; Tp = wave period).

Sea state	Hs (m)	Tp (s)
1	1.5	8
2	2.0	8
3	2.5	6
4	2.5	8
5	2.5	10

Acceleration data were according to a right-handed coordinate system, with the x-axis (longitudinal nacelle axis) along the direction of incoming waves, the y-axis (lateral nacelle axis) perpendicular to this in the horizontal plane and the z-axis along the vertical direction. Acceleration data were simulated with a sample rate of 10 Hz. In the calculations of the predicted motion sickness, the maintenance engineers were assumed to be aligned with this coordinate system, facing the direction of the positive x-axis. Figure 2 shows examples of 3 DoF acceleration data for both base types with a sea state of Hs = 2.5 m and Tp = 8 s. As can be seen from the figure, longitudinal and vertical accelerations were of higher magnitude for the semisubmersible base, while the TLP base showed higher accelerations in the lateral direction.

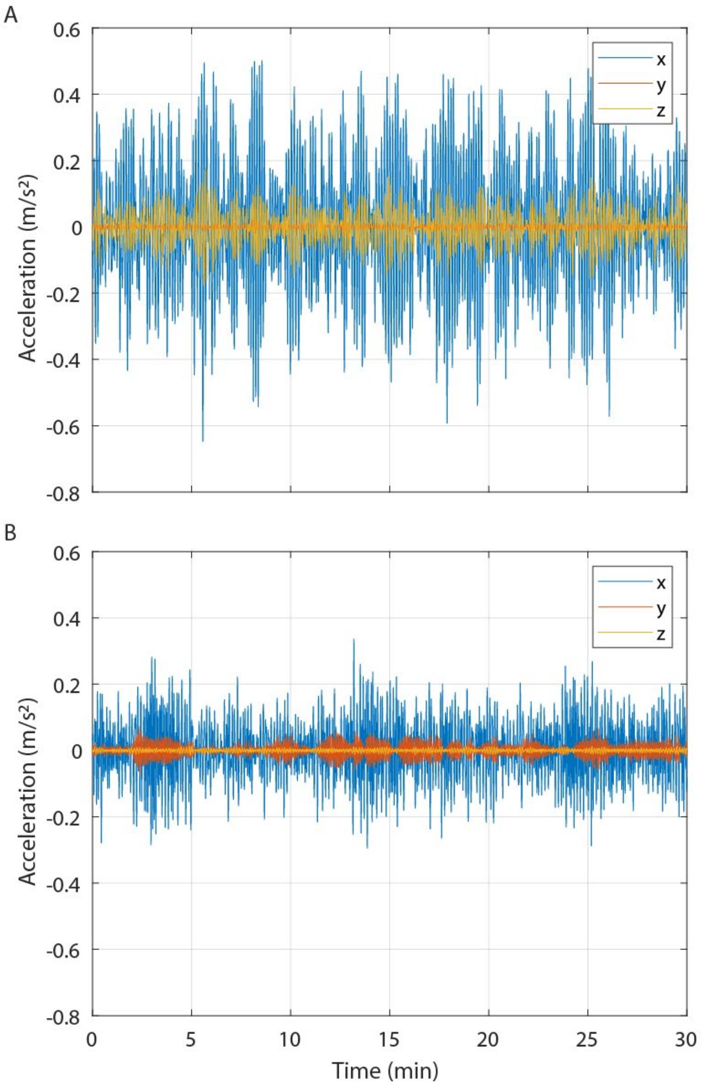

Figure 2. Examples of nacelle acceleration data with sea state Hs = 2.5 m and Tp = 8 s. A. Semisubmersible base. B. TLP base.

4 Results

4.1 Motion Sickness Dose Values

Motion sickness dose values for the five sea states and the two bases were computed based on both the TNO model (Figure 3) and the ISO 2631-1 (Figure 4). Both models estimated higher MSDV values for the semisubmersible base compared to the TLP base. While both models predicted similar patterns of MSDV for the different sea states, the predicted MSDVs from the ISO model were slightly higher than those from the TNO model, in particular for the semisubmersible base. For a wave period Tp = 8 s, MSDVs increased with wave height Hs. However, Tp showed a non-linear effect for a given wave height Hs of 2.5 m. For both base types, the highest MSDVs were predicted for Tp = 8 s, while both 6 and 10 s produced lower MSDVs. The difference between MSDVs for different wave heights was smaller for the TLP base than for the semisubmersible base.

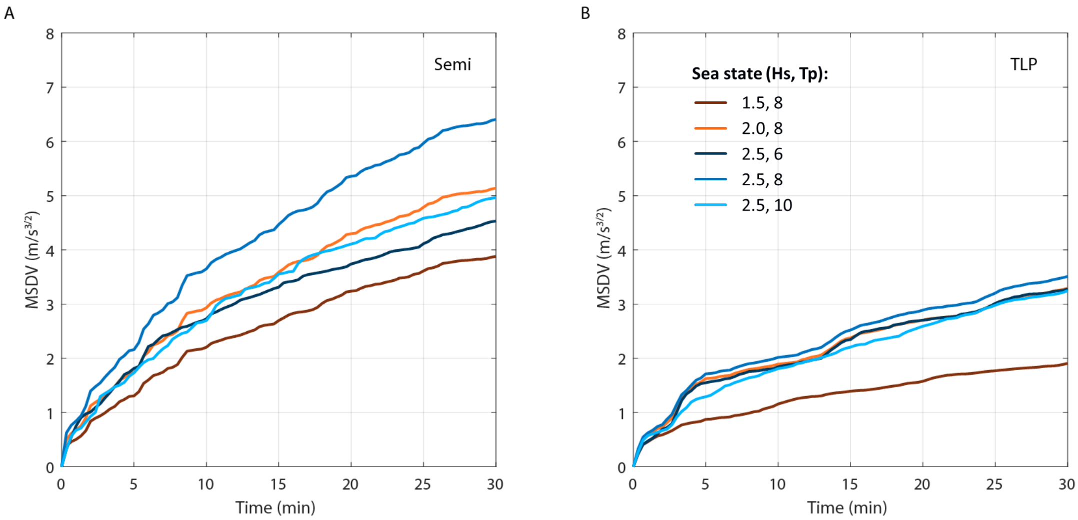

Figure 3. Motion sickness dose values based on the TNO model for five different sea states. A. Semisubmersible base. B. TLP base.

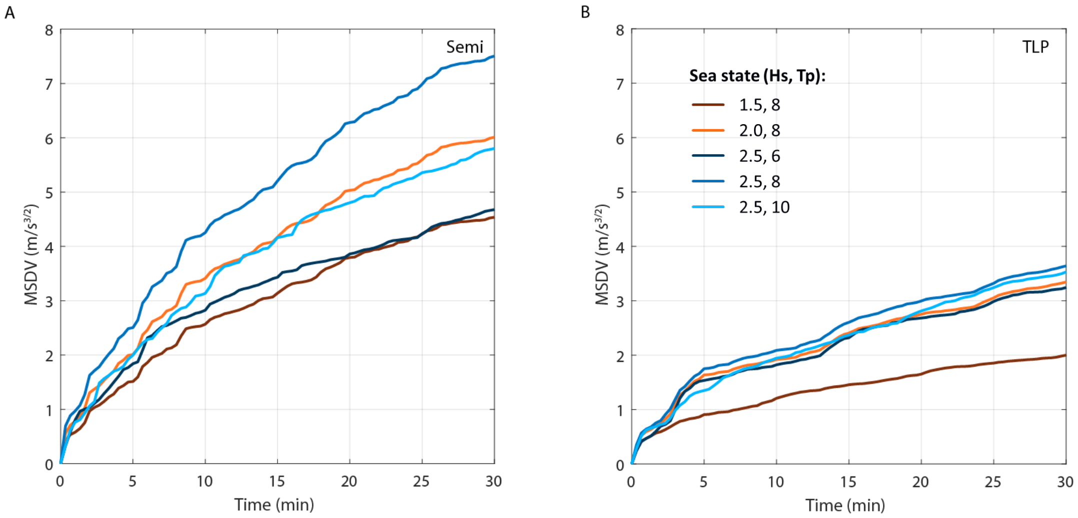

Figure 4. Motion sickness dose values based on the ISO 2631-1 model for five different sea states. A. Semisubmersible base. B. TLP base.

4.2 Motion sickness predictions

Motion sickness predictions from both models (P(MISC > c) for the TNO model and MSI for the ISO 2631-1 model) based on the acceleration data for 30 minute exposure durations all provided very low numbers, not allowing for a clear distinction between bases and sea states. Therefore, the MSDVs were extrapolated to an exposure duration of 3 hours and motion sickness predictions were compared for this duration. As can be seen from Figure 5, the predicted P(MISC > c) decreased with increasing values of *c*, indicating that the more severe the motion sickness symptoms, the lower the proportion of people expected to reach that severity due to exposure to the nacelle motion caused by the given sea state. For the submersible base, just over half the people would be expected to suffer at least some motion sickness with most sea states, while this proportion was just below 0.5 for the TLP base. The proportions of people expected to experience some degree of nausea (P(MISC > 5) were just above and below 5%, respectively, for the two base types. The proportion of people expected to reach emesis predicted by the TNO model (P(MISC > 9) was about zero for both base types, while the MSI from the ISO model was slightly higher (between 0 and 5%, see open squares for c = 9 in Figure 5).

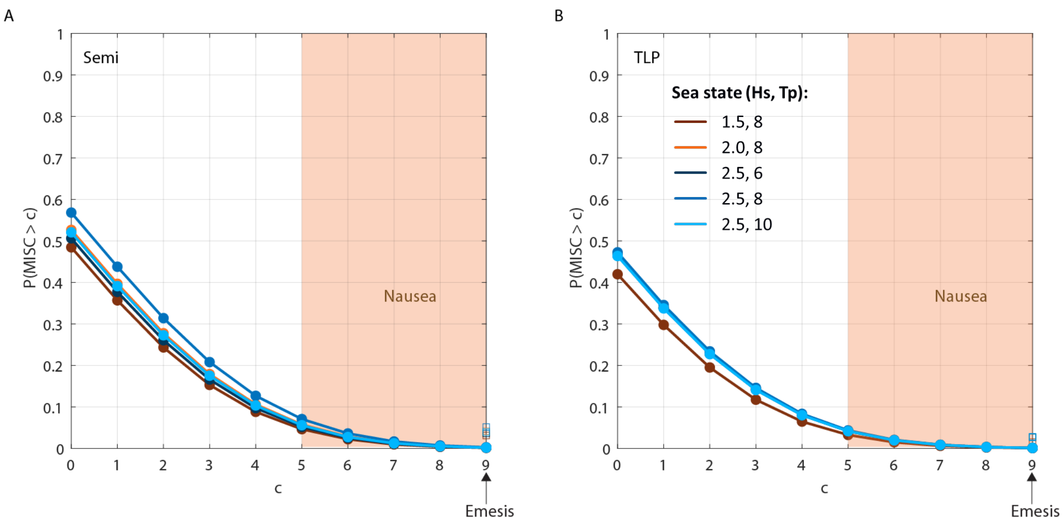

Figure 5. Motion sickness predictions. A. Semisubmersible base. B. Tension Leg Platform base. The vertical axis shows the proportion of people expected to report a MISC value > criterion *c*, with *c* along the horizontal axis. P(MISC > 5) indicates the proportion of people expected to experience nausea (shaded area), while P(MISC > 9) indicates the proportion of people expected to vomit. Lines and filled circle symbols show the predictions from the TNO model for different sea states, while the open squares at c = 9 give the MSI predictions from the ISO model.

5 Discussion

Two motion sickness prediction models were used to assess the likelihood of motion sickness in maintenance engineers working in the nacelle of a wind turbine with a floating base. The ISO 2631-1 model predicts the proportion of people expected to reach emesis (vomiting). While the original model only takes vertical accelerations into account, the model was generalised to three motion axes to provide predictions for motion sickness in a floating wind turbine. The TNO model is an extended version of the ISO model, which does not only take 3 DoF accelerations into account but is also able to predict along the entire range of motion sickness symptoms. In fact, it was based on pre-emesis data and predicts emesis by extrapolation.

Both models predicted very low probabilities of motion sickness for both base types that were evaluated, a semisubmersible base and a TLP base. The Motion Sickness Dose Values indicated a higher probability of motion sickness with a TLP base compared to the semisubmersible base. For both base types, motion sickness was predicted to be more likely for higher wave heights at a constant wave period. However, the effect of wave period was found to be non-linear, with Tp = 8 s producing the highest MSDVs (and hence the highest probability of motion sickness), while periods of 6 and 10 s were predicted to cause less motion sickness (at the same wave height Hs = 2.5 m). The TNO model predicted that after 3 hours of exposure to the different nacelle acceleration profiles, about 50% of people with an average motion sickness susceptibility would be expected to report some form of motion sickness symptoms (regardless of severity). This percentage was again slightly higher for the semisubmersible base compared to the TLP base. The percentage of people expected to feel nauseous was just above and below 5% for the semisubmersible and TLP bases, respectively, while the percentage of people reaching emesis was predicted to be very close to zero for both base types. The ISO model predicted a slightly higher likelihood of emesis (around 5%).

Both models have several limitations and assumptions that have to be kept in mind when interpreting these results. The ISO 2631-1 model was developed to predict seasickness aboard large ships and was formulated based on vertical accelerations only. While we have generalised this model to 3 DoF here, assuming equal contributions of the three motion axes, this has not been validated. Moreover, the model assumes that the proportion of people reaching emesis is linearly related to the estimated Motion Sickness Dose Value, which in reality cannot apply to extreme MSDV values, as this would lead to predicted proportions above 1. Similarly, it may be questioned whether this approximation holds for low MSDV values as observed here. The TNO model uses a non-linear probability model to relate the likelihood of motion sickness to the MSDV and therefore does not suffer from this limitation. However, as it was based on motion sickness data up to MISC values of 7 (moderate nausea), predictions concerning emesis are by extrapolation and have not been validated. Moreover, the TNO model is based on data from motion exposures up to about 30 minutes. Consequently, predictions for exposure durations of several hours should be treated with caution.

Compared to the magnitude of accelerations normally required to provoke seasickness or carsickness, the accelerations computed for the wind turbines are relatively mild and therefore lead to low predicted probabilities of motion sickness. However, observations concerning motion sickness in high-rise buildings suggest that this may underestimate the actual likelihood of motion sickness. Similar to floating wind turbines, high rise buildings sway in the wind and this is known to result in motion sickness symptoms in their occupants despite relatively low levels of acceleration [5]. Possibly, the expectation that buildings do not move may enhance the sensory conflict underlying motion sickness, therefore leading to more motion sickness than when the same physical acceleration would be experienced in a vehicle such as a passenger car or ship. Something similar might hold for wind turbines. However, in the absence of empirical motion sickness data for people in wind turbines this is currently a hypothesis that awaits testing.

In general, the lack of empirical data concerning both how much floating wind towers actually move given a certain sea state and the motion sickness this results in constrains the usability of the current results. The model predictions do highlight certain qualitative trends in motion sickness as a function of both wave height and wave period that make further research both necessary and interesting.

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