

FLOATING OFFSHORE WIND
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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

COM04: THE TECHNICIAN'S PERSPECTIVE

Public Summary Report



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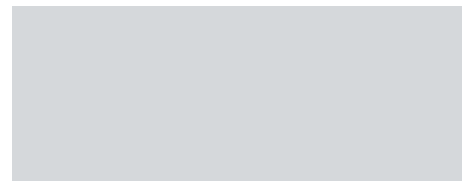
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EXECUTIVE SUMMARY

Floating offshore wind turbines (FOWTs) present a unique challenge over bottom fixed foundations: the environment in which technicians will perform their maintenance tasks will be constantly moving. This could lead to a reduction in technician performance, due to the potential for motion sickness. This report addresses the challenges of motion and motion sickness through 4 work packages which seek to answer the following questions:

1. What is the current state-of-the-art for motion sickness theory and guidance applicable to floating offshore wind (FOW)?
2. What character of motion can be expected at the nacelle of FOWTs?
3. Does motion sickness affect technicians working on already-existing FOWTs at the demonstrator sites in the UK?
4. How might further research into the effects of nacelle motion on human operators be performed?

Theory and Guidance Review and Stakeholder Engagement

Motion sickness occurs when there's a mismatch between the brain's motion receptors. This happens when the expected combination of visual and motion signals gets confused in a moving environment, triggering a response similar to poisoning. Symptoms of motion sickness can vary widely, including pale skin, stomach discomfort, lethargy, low mood, and, most notably, vomiting. The likelihood of experiencing motion sickness depends on the amplitude and frequency of the motion, as well as the duration of exposure. The most likely frequency to cause motion sickness is around 0.167 Hz.

There are three standards that provide guidance on motion sickness, which may be relevant for FOW applications. The most commonly used in FOW research is the NORDFORSK guidance. This standard sets limits for root mean squared values of acceleration data in horizontal and vertical directions, as well as roll motion. However, it may not be entirely suitable since it was originally designed for merchant and navy vessels, focusing on a ship's ability to maintain position. Similar issues may arise with the guidance provided in STANAG 4154. Additionally, obtaining the primary documentation for both sets of guidance can be challenging. The most appropriate standard for assessing motion sickness might be ISO 2631-1, which addresses whole body vibration. This standard considers the frequency, magnitude, and duration of motion by calculating a motion sickness dose value, which can then be used to predict sickness outcomes.

Engagement with stakeholders informed a wide-ranging discussion. Broadly, stakeholders anticipate some degree of motion sickness amongst technicians, but there was less agreement on the extent to which this would reduce technician performance. In general, it was thought that motion sickness will depend on the floating foundation type, due to the different motions that this will cause at the nacelle. Stakeholders also expected that habituation to motion will be a significant factor in the extent of motion sickness amongst technicians. The prevailing consensus that habituation occurs after three days of motion exposure should mean that technicians do not feel as motion sick as some guidance would suggest. However, habituation benefits depend on the similarity between the motion felt on the service vessels and the FOWT.

While the incapacitation of technicians due to motion sickness is a clear risk, stakeholders are more concerned about the impact of milder symptoms, especially fatigue and the related Sopsite syndrome (motion induced lethargy). Fatigue can reduce the performance of secondary tasks, raising safety concerns. This issue may be exacerbated by other factors related to motion. Living in a moving environment is known to require additional energy expenditure. Furthermore, the distance from shore of future FOWTs may necessitate longer shift rotations, increasing the time spent in this challenging environment.

Numerical Modelling

Within OrcaFlex, models were created of a 15 MW semisubmersible floating turbine, and a 15 MW tension leg platform (TLP) floating turbine. Additionally, a 10 MW bottom fixed turbine was also created, to provide a baseline of current conditions for offshore technicians. The programme was used to subject each model to wind and wave conditions derived from recorded conditions at locations where floating turbines are likely to be located. The motion of the nacelle over the time history was then analysed to determine the frequency and magnitude of acceleration in X, Y and Z directions. Current standards were also applied to the time history to provide an estimate of workability.

The maximum root mean squared (RMS) acceleration in the X direction for all turbine models considered is shown in Table i, along with the maximum predicted motion sickness incidence (MSI), calculated via the ISO Standard ISO:2631-1 [3]. The results indicate that motion sickness for FOWTs is not anticipated to be a significant risk, and is likely to be similar to that experienced at present on bottom fixed offshore wind turbines (BOWTs). Additionally, the results suggest that the TLP motion results in less motion sickness than the semisubmersible. However, the applicability of this result to TLP and semisubmersible designs more generally is not certain; the main driver of nacelle motion is platform heave and pitch, and semisubmersible have different responses depending on their design.

Table i: Maximum acceleration in X direction for all turbine models alongside the predicted motion sickness incidence (MSI)

	BOWT RMS (g)	Semisub RMS (g)	TLP RMS (g)	BOWT MSI (% vomiting)	Semisub MSI (% vomiting)	TLP MSI (% vomiting)
Generating	0.049	0.031	0.031	9.9	6.8	10.7
Idling	0.060	0.020	0.009	16.8	6.5	2.7
Parked	0.032	0.020	0.010	7.8	6.4	3.1

However, it should be noted that the conclusions surrounding motion sickness are based on an incorrect application of the ISO standard (which only accounts for vertical motion). This was necessary as there are no other standards which exist to assess motion sickness due to horizontal motion. This is identified as a significant gap which if filled could improve the confidence in the outcome of this report.

Technician Experience

We engaged with two floating demonstration projects:

- **Kincardine**, located off the coast of Aberdeen, consists of five turbines mounted on Windfloat semi-submersible foundations provided by Principle Power. Nacelle maintenance is performed by MHI Vestas; and
- **Hywind**, located off the coast of Peterhead, consists of six spar turbines, and is owned by Equinor and serviced by Siemens Gamesa.

Semi-structured interviews were performed with technicians from Kincardine, previous technicians from the Hywind farm, and a managerial team from a fixed offshore farm who utilise an SOV to carry out construction and maintenance activities. The interviews revealed information across three categories:

Turbine design has significant impact on motion felt at nacelle level.

Little motion was reported on Kincardine turbines, largely credited to the active ballasting and heave plates of the foundation. Hywind, conversely, had significant nacelle motion. This suggests that turbine design has a direct impact on technicians; awareness of this can then help influence future design considerations

Quality offshore living conditions are essential for technician morale and well-being.

Engagement with an SOV team shared how SOVs benefit from less motion, minimising motion sickness. The team's policy to seek safe waters in adverse conditions is in place as a more productive and cost-effective method, trading the added transit time for a healthier crew. This points to the importance of vessel design in relation to technician well-being.

Motion sickness has a noticeable effect on FOW technicians.

Felt on the crew transfer vessel (CTV) and spar turbine design, motion sickness was a recurring concern for FOW technicians. Anti-nausea medication was used to mitigate the effects, and there was an observable drop in motion sickness after acclimation.

Review of Approaches to Laboratory Testing

A review was performed of current guidance on human-subject testing and facilities in which this type of testing can be performed. The results of this review suggest a number of aspects which should be taken into consideration in any future laboratory-based testing of the effects of FOWT nacelle motion.

The necessary sample size to statistically answer the research question

The exact research question that the experiment is attempting to answer should be explicitly defined at the outset. This will allow the necessary sample size of participants and testing requirements to be calculated. For instance, if trying to prove a statistically significant result, a large number of participants may be necessary to define statistical distribution of results. Additionally, different characteristics which are known to affect an individual's susceptibility to motion sickness, such as sex and age, should be considered as part of this sample definition exercise. The likely impact of the proposed testing duration on participant recruitment should also be considered in this stage.

Safety and well-being of participants

Any research with human participants needs to be adequately planned from a safety and ethical point of view to minimise any risk of harm. For this type of research, this planning would need to include:

1. Screening of participants for pre-existing conditions,
2. H&S within the testing apparatus, and
3. Consideration of emergency procedures.

The choice of motion simulator

A review of motion simulators in the market identified several that are capable of completely replicating the motion simulated at a FOWT nacelle, as indicated by the green boxes in Table ii. However, these machines are expensive to hire and located within research and testing facilities in Europe, necessitating contracting with these organisations, and recruiting participants who either live near that facility or are capable of travel to it. At the same time, there are several simulators located within the UK and available at a cheaper rate, yet do not have the range of motion to completely replicate the most extreme simulated nacelle motion, and would therefore need to “clip” the replicated motion. Selection of a motion simulator should therefore consider the implications of this clipping on the accuracy of the results.

Table ii: Comparison of motion simulator range of motion. Green indicates ability to replicate modelled nacelle motion. Red indicates that the modelled motion is beyond simulator's capabilities.

Motion Type	FLOWIC Centre Hexapod	Cybermotion Simulator	Cable Robot Simulator	Desdemona	Limousine	SLINE 3DoF
Surge (m)	Red	Green	Green	Green	Green	Red
Sway (m)	Green	Green	Green	Red	Red	Red
Heave (m)	Green	Green	Green	Green	Red	Red
Surge vel. (m/s)	Light Blue	Light Blue	Light Blue	Light Blue	Green	Red
Sway vel. (m/s)	Light Blue	Light Blue	Light Blue	Light Blue	Red	Red
Heave vel. (m/s)	Light Blue	Light Blue	Light Blue	Light Blue	Red	Red
Surge accel. (m/s ²)	Green	Light Blue	Green	Light Blue	Green	Red
Sway accel. (m/s ²)	Green	Light Blue	Green	Light Blue	Red	Red
Heave accel. (m/s ²)	Green	Light Blue	Green	Light Blue	Red	Green
Roll (°)	Green	Green	Green	Green	Red	Green
Pitch (°)	Green	Green	Green	Green	Red	Green
Yaw (°)	Green	Green	Green	Green	Red	Red

The test type and data collection

The review suggested a range of tests which can be performed to assess the effect of motion on a number of human functions. These can be categorised into four sections:

- Dexterity (fine motor skills and balance) which correlate to the impact on technicians' ability to carry out tasks. Examples include pegboard tests and walking experiments.
- Cognitive ability, generally through the form of answering questions or task management, evaluate problem solving, response time, and memory. Examples include psychomotor vigilance testing.
- Biofeedback, or the involuntary body response to stimuli, includes heart rate, eye motion, electrocardiograph, and skin temperature. Examples include monitoring heartrate and sweat.
- Surveys, which allow for assessing subjective experiences (e.g. dizziness and nausea) not otherwise tracked. Examples include the MISC survey widely used in academic research.

Additional Commissioned Work

To address some of the challenges raised above regarding the lack of a suitable guidance to assess the likelihood of motion sickness from horizontal motion and account for milder symptoms than vomiting, additional work was commissioned with the research organisation TNO who have developed a proprietary model to overcome these limitations. Broadly, the results from the TNO analysis are in agreement with the results of the assessment using the ISO standard, namely that expected motion sickness incidence from the nacelle motion modelled is low (less than 10% of a standard population experiencing nausea in the most provocative motion).

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NOMENCLATURE

BEM	Blade Element Momentum
BOWT	Bottom Fixed Offshore Wind Turbine
CTV	Crew Transfer Vessel
DLL	Dynamic Link Library
DoF	Degree of Freedom
FLOWIC	Floating Offshore Wind Innovation Centre
FOW	Floating Offshore Wind
FOWF	Floating Offshore Wind Farm
FOWT	Floating Offshore Wind Turbine
Hs	Significant Wave Height
HV	High Voltage
IEA	International Energy Agency
ISO	International Organisation for Standardization
MSDV	Motion Sickness Dose Value
MSI	Motion Sickness Incidence
MSSQ	Motion Sickness Susceptibility Questionnaire
NPD	Norwegian Petroleum Directorate
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
PSD	Power Spectral Density
RMS	Root Mean Squared

ROSCO	Reference Open Source Controller
RWT	Reference Wind Turbine
SOV	Service Operations Vessel
TLP	Tension Leg Platform
Tp	Wave Peak Period
VR	Virtual Reality
WMA	World Medical Association

1 INTRODUCTION

The nacelles of floating offshore wind turbines (FOWTs) are expected to move more than conventional bottom fixed offshore wind turbines due to the increased compliancy of the structure. This increased motion may make the technicians working on FOWTs motions sick. Motion sickness is known to be a significant challenge in other industries and sectors, where it can have a negative effect on human operators wellbeing and ability to carry out primary and safety-related tasks effectively.

At present, the scale of this potential challenge for floating offshore wind (FOW) is unknown. The degree of movement in a FOWT nacelle, and the effects of that movement on a human being are both uncertain and unquantified. The aim of this project is to investigate the issue of motion sickness on FOWTs in a systematic manner. The project seeks to address four key research questions:

1. What is the current state-of-the-art for motion sickness theory and guidance applicable to FOW?
2. What character of motion can be expected at the nacelle of FOWTs?
3. Does motion sickness affect technicians working on already-existing FOWTs at the demonstrator sites in the UK?
4. How might further research into the effects of nacelle motion on human operators be performed?

These four research questions were addressed via four work packages, presented in the following sections of the report. The conclusions from these work packages provide insightful findings regarding the current understanding of the risk of motion sickness on FOWTs, and highlights methods and approaches which could be used in the future to explore the unique motion challenges of FOWT nacelles in a controlled experimental setting.

2 LITERATURE AND GUIDANCE REVIEW

A literature review and stakeholder engagement was first performed to establish the current consensus on the risk of motion sickness in a FOW setting. A review of academic and grey literature established the current leading theory on the causes of motion sickness, and identified any relevant research for the question of motion sickness in environments similar to FOWT nacelles. The review also highlighted any relevant guidance for assessing the risk of motion sickness.

To supplement this review, a stakeholder engagement exercise was conducted to investigate the current industry and academic outlook on the motion-based challenges of FOW. A summary of stakeholders who provided input is presented in Table 1. ORE Catapult would like to thank them for their contribution.

Table 1: Stakeholders engaged with for report.

Organisation	Representatives	Area of expertise
University of Westminster	Professor John Golding	Motion sickness
Boston Energy	Colin Pearce	Technician recruitment
Robert Gordon University	Ruby Roberts	Human factors in offshore wind
Tidal Transit	Leo Hambro	CTV transfer
Aventus Energy	Ross Thompson, Stuart Paterson	O&M provider
University of Iceland	Professor Hannes Petersen	Motion sickness
Maritime and Coastguard Agency	Pete Lowson	Regulation
BP	Mathew Bramwell	Offshore wind development
SSE	Marcus Booth, Rachel Lawrence	Offshore wind development
University of Hull	Dr Stefi McMaster	Fatigue
American Bureau of Shipping	Anton Janssens, David Davenport Jones, Kevin McSweeney, Jevon Chan	Standards Provider

2.1 Theory of Motion Sickness

Motion sickness has been studied scientifically for decades, with a focus on sea sickness as this is the most common form of motion sickness. Air sickness and space sickness have also been studied, due to their effects on military operations. Much of the work on motion sickness has been on theories for its cause, and physical experiments on both human and animal subjects to determine the most provocative types of motion.

Throughout literature, the widely accepted theory of the cause of motion sickness is that of sensory mismatch [1] [2]. The brain receives signals about its position and movement relative to the ground via several inputs: the eyes, the body (through forces acting on the muscles and skeleton), and signals from the vestibular system (located in the inner ear), which provide both linear and rotational acceleration responses. As a person moves on land, the response that they receive from these systems are aligned. For example, if someone moves their head, the signals received from the vestibular system matches what would be expected given the signals received from the eyes and muscles. The aligned signals indicate that there isn't a problem, and so no poor outcome occurs.

If, however, a person is in a moving environment, the signals received from the different receptors will not align as expected. For instance, a person reading below deck in a boat at sea will receive signals from their eyes that there is no movement, but will receive signals from their vestibular and muscular systems that there is movement. There is then a mismatch between the expected response (no movement) and the received response (movement). According to theory, the body interprets this

mismatch as a symptom of poisoning, leading to several poison-like responses. The response is not immediate, but instead is cumulative – each mismatch adds a little dose of “poison.” The longer a person is exposed to the motion, the greater the dose of motion sickness. As the poison adds up, the response becomes gradually more severe, until vomiting is reached.

There are a range of symptoms caused by motion, varying in severity. The most obvious sign is vomiting and nausea, however a person may also suffer from stomach awareness, malaise, dizziness, cold sweats, heartburn and low mood [3] [4]. During discussions with academics, it was suggested that the malaise response – known as “Sopite syndrome” was often overlooked in research. This response makes individuals feel fatigued and sleepy, but does not necessarily inhibit their ability to perform tasks which they give attention to, termed “primary tasks”. However, if a task becomes familiar, performance may drop when experiencing motion sickness [5].

Regardless of the symptoms, after a certain period of time the degree of motion sickness reduces as the individual becomes “habituated”. This process often takes several days, and is colloquially known as “getting one’s sea legs”. According to the sensory mismatch theory, during this time, the brain learns to “expect” different responses from the receptors. For instance, the movement of a sailing boat in a mild sea will create a moving environment in which the interactions of the signals from the eyes, vestibular system and body can be predicted to some degree. The individual then becomes habituated to this motion. If the person moves to an environment with a different motion character, there is again mismatch between sensory signals, and the individual will again become seasick. This is true even when moving to firm land – a phenomenon known as “Mal de Débarquement” – when a person feels like the ground is moving. The extent to which moving from one environment to another induces motion sickness depends on the similarity of motion in the two environments.

The potential for a motion to cause motion sickness depends on the amplitude and frequency of the motion. Numerous studies on both animals and humans have shown that lower frequency excitations, under approximately 1 Hz, elicit motion sickness responses, whereas motions above this frequency do not [1]. The magnitude of the motion acceleration, and the duration of exposure to this motion (the “dose”) also increases the severity of motion sickness.

There is currently some debate over whether the direction of motion affects the sickness response. The foundational piece of work in the study of the relationship between motion character and motion sickness was performed in the 1970s by James O'Hanlon and Micheal McCauley [6]. They placed healthy male subjects in an enclosed box and oscillated it in the vertical direction, varying the frequency and acceleration values, and counted the percentage of subjects who vomited in a two hour period [6]. This work derived a model predicting motion sickness incidence (MSI), the proportion of a population that would vomit from motion sickness, from a motion's acceleration and frequency. The model suggests maximum MSI at a frequency of 0.167 Hz, the basis for current standards (discussed later), shown in Figure 1. However, work subsequent to this has indicated that acceleration in directions other than the vertical can also induce motion sickness, with some indicating that acceleration in the horizontal may be more provocative than the vertical [7]. The peak frequency for inducing vomiting in this direction is similar at 0.2 Hz.

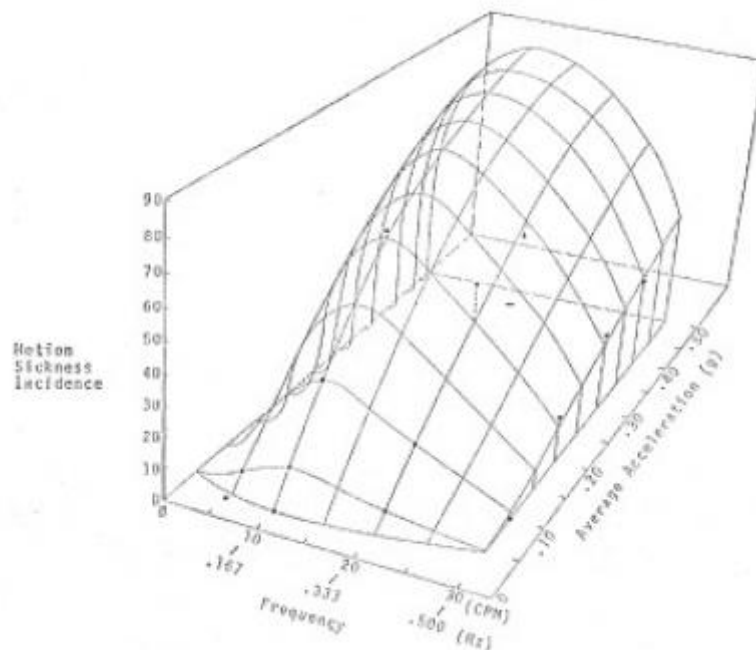


Figure 1: Relationship between motion sickness incidence, frequency, and acceleration. From [6].

2.2 Published Guidance

There are a small number of pieces of published guidance related to assessing the risk of motion sickness in a given moving environment. Previous work researching motion sickness on FOWTs have made use of several of these, Table 2. These pieces of guidance are next reviewed.

Table 2: Workability guidance used in recent FOW research

Paper	Year	Guidance used
Scheu et al. [8]	2018	NORDFORSK, ISO 2361-1
Jenkins et al. [9]	2021	NORDFORSK
Kaptan et al. [10]	2022	NORDFORSK
Floating wind Joint Industry Programme Phase 4 [11]	2022	NORDFORSK, Illness rating

2.2.1 NORDFORSK Guidance

The NORDFORSK guidance is the most ubiquitously used in research related to FOW, and other areas such as service vessel design [12]. The guidance is concerned with the root mean squared (RMS) value of roll motion and accelerations in the vertical and horizontal directions, and applies limits for different types of vessels, presented in Table 3. The guidance also gives limiting motions for different types of work, Table 4. The description of these types of work is provided in [13] [14]:

- **Light manual work.** Work carried out by people adapted to ship motions. Not tolerable for longer periods. Causes quickly fatigue.
- **Heavy manual work.** For instance, on fishing vessels and supply ships.
- **Intellectual work.** Work by people not so well adapted to ship motions. For instance, scientific personnel on ocean research vessels. Work of a more demanding nature. Long-term tolerable for the crew.
- **Passengers on a ferry.** People unused to ship motion and exposed to symptoms of motion sickness.
- **Passengers on a cruise liner.** Older people close to the lower threshold below which vomiting is unlikely.

Table 3: NORDFORSK limiting motions for vessels

Parameter	Merchant Ships	Naval Vessels	Fast small craft
Vertical acceleration at forwards perpendicular (RMS)	0.0275g (L<100m), 0.05g (L>330m)	0.275g	0.65g
Vertical acceleration at bridge (RMS)	0.15g	0.2g	0.275g
Lateral acceleration at bridge (RMS)	0.12g	0.1g	0.1g
Roll (RMS)	6.0°	4.0°	4.0°

Table 4: Limiting motions based on type of work

Task	Vertical Acceleration (RMS)	Lateral Acceleration (RMS)	Roll (RMS)
Light manual work	0.2g	0.1g	6.0°
Heavy manual work	0.15g	0.07g	4.0°
Intellectual work	0.10g	0.05g	3.0°
Transit passengers	0.05g	0.04g	2.5°
Cruise Liner	0.02g	0.03g	2.0°

Although often quoted in research, the original source for this guidance, *Assessment of ship performance in a seaway. Results of a Nordic co-operative project on seakeeping performance of ships*, is not available electronically. Obtaining the original reference document is difficult, as one stakeholder told of how they needed to attend the Library of Copenhagen in person to do so. Recently, a critical review of seakeeping criteria revealed information about the origin of the standard [14]. The standard was devised as part of a co-operative Nordic project on seakeeping, and was created from literature reviews of merchant and naval vessel capabilities in different seaways

[15]. It is predominantly based upon the ability of different ships to maintain their speed and position in different weather conditions, and is focused on naval and merchant ships. However, the distinct between these two vessel types is not clear.

The report does include a brief consideration of human factors, however the basis for the limits is unclear. Motion can affect people in multiple ways, causing them to become motion sick, but also causing them to lose their balance, or expend additional energy compensating for the movement of their environment. Each of these effects may be induced by different types of motion, and as the guidance does not state this “motion-impact” mode with the limits, they are of limited value when assessing FOW motion.

Regardless of the “motion-impact” mode, it has been suggested that some of the limits in the guidance are not realistic. The vertical acceleration limit of 0.2g for light manual work corresponds to nearly 2 m/s², and the roll of 6° is equivalent to an incline of 10%. Some literature has suggested that it is impossible to conduct the type of work suggested in the standard at the prescribed limits [16].

In assessing motion sickness, it is unlikely that the NORDFORSK will be applicable. The degree to which a person suffers from motion sickness depends not only on the magnitude of the motion, but also on the frequency of that motion, and on the length of time that the person has been exposed to it. As neither of these parameters are considered, NORDFORSK cannot be used to make an explicit judgment about motion sickness.

2.2.2 STANAG 4154 Guidance

Another commonly cited assessment criteria for assessing the workability of FOW is the NATO Standardization Agreement (STANAG) 4154: *Common Procedures for Seakeeping in the Ship Design Process* guidance. The criteria is presented in Table 5. STANAG 5154 does explicitly mention motion sickness and sets a motion sickness incidence level of 20%, including a time period of motion dose. However, it is unclear whether this should be calculated prior to ship construction or from observation once the ship has been built and is working in the field.

Table 5: STANAG 5154 motion sickness criteria

Criteria	Limit
Motion Sickness Incidence	20% of crew in 4 hours
Motion induced interruptions	1/min
Roll	4 ° (RMS)
Pitch	1.5 ° (RMS)
Vertical acceleration	0.2g (RMS)
Lateral acceleration	0.1g (RMS)

As with the NORDFORSK guidance, the origin and applicability of this guidance for FOW is not clear. Although the guidance is quoted in several places in the literature, it has not been possible in this current report to locate the guidance. Indeed, the document appears to be a classified military document.

Apart from the challenges in ascertaining the original guidance, there are also concerns regarding its use for FOW applications. Several stakeholders, and elements of literature have suggested that as the standard is designed for military ships, with naval personnel on board, it is unlikely to be suitable for applications outside of this narrow remit. Additionally, as with the NORDFORSK standard, questions have been raised about the limits themselves, suggesting that the acceleration and roll limits may be unrealistic [12] [16].

2.2.3 ISO 2631-1

The most relevant standard for motion sickness at present is the International Organisation for Standardization (ISO) 2631-1 Standard: *Mechanical vibration and shock – evaluation of human exposure to whole-body vibration* [17]. The standard provides guidance for assessing many different types of vibration at a range of frequencies, with specific sections for motion sickness consideration. The standard considers that motion sickness is only induced by motion in the vertical direction at a frequency of less than 0.5Hz.

To estimate the effects of motion sickness, the standard provides a method to calculate a motion sickness dose value (MSDV), which accounts for the magnitude of motion, the frequency of motion, and the duration of exposure to that motion:

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

Where $a_w(t)$ is the frequency weighted acceleration in the z (heave) direction, and T is the total period of interest in seconds. The filters to apply the frequency weighting to the acceleration data are described in appendix A of the standard, with a maximum weighting value at a peak of 0.16 Hz [17]. A representation of the frequency weighting is provided in Figure 2. Once calculated, the MSDV can be used to estimate how the motion will impact people within that environment by applying a factor, K_m , to it. For instance, the MSDV can be used to estimate the MSI:

$$MSI = K_m \times MSDV \quad (2)$$

Applying $K_m = 1/3$ for a mixed population of males and females.

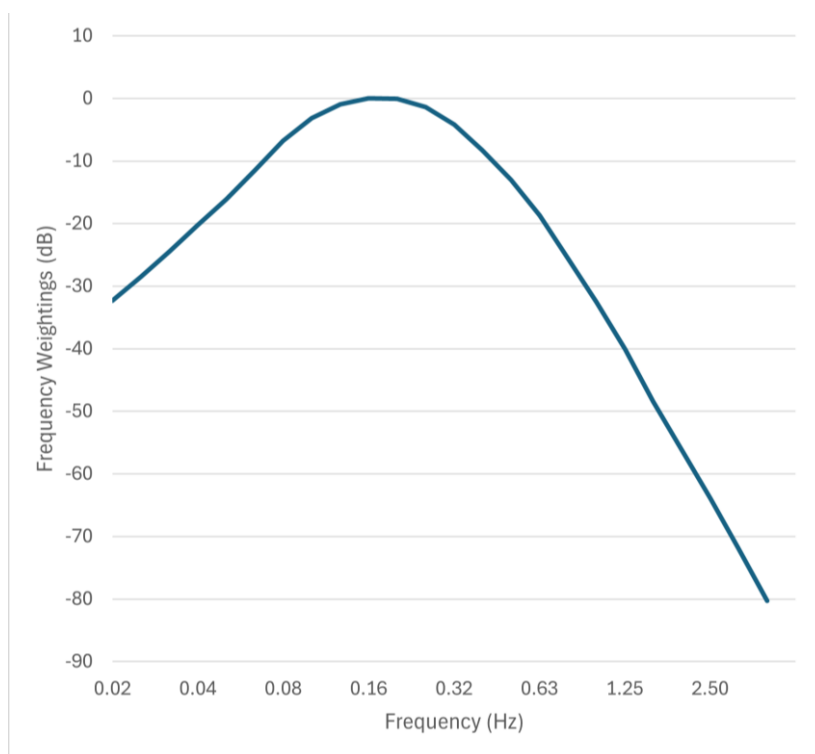


Figure 2: Representation of ISO 2361-1 frequency weighting graph

The standard is based upon work mentioned previously by James O'Hanlon and Micheal McCauley, in which male subjects were placed in an enclosed box, and oscillated in a vertical direction at different frequencies and amplitudes until they vomited. It also draws upon work which monitored the motion of large ferries, and the prevalence of seasickness to derive a quantitative relationship between motion and motion sickness. This work found that heave motion was most strongly correlated with motion sickness.

The origin of the standard can provide context and suggest its suitability for different motion environments. As the original physical experiments only considered movement in the z-direction, and the recorded data was from ferries, which are likely to move more in the heave direction than others, it follows that the standard only considers heave motion. The standard is therefore likely to be applicable to environments which move in a similar way. For instance, the American Bureau of Shipping requires its use in assessing passenger comfort on ships [18].

However, while the standard may be effective for ships, the focus on vertical motion is unlikely to be appropriate for environments where this is not the dominant direction of motion [19]. As was discussed in Section 2.1, oscillation in the horizontal direction may be more provocative than vertical motion, which is likely to be a problem for FOWTs, where movement of the nacelle is expected to have a significant horizontal component. Motion sickness in similar environments was mentioned by stakeholders, such as “skyscraper sickness”, where the wind induced motion of tall buildings leads to motion sickness symptoms. Additionally, some stakeholders knew of technicians who had experienced motion sickness in bottom fixed turbines where motion is all in the horizontal plane.

As well as the sole consideration of vertical motion, another critique of the ISO 2631-1 standard is its focus on emesis (vomiting). While vomiting is the most observable consequence of motion sickness, there are other symptoms, noted in Section 2.1, which could have a degrading effect on technician performance. These symptoms are likely to occur at lower MSDV values, so the use of $1/3$ for K_m will provide an unrealistically positive expectation of the effects of motion sickness.

To overcome these limitations, variations on the standard have been proposed within the literature. For instance, to estimate the degree of malaise caused by a motion sickness dose value, it has been proposed to use a K_m value of 0.02 instead of 1/3, with the resulting number an “illness rating” between 0 (“absolutely fine”) and 4 (“absolutely dreadful”) [20]. Additionally, several authors have suggested applying the standard to acceleration data in the x and y directions. However, there is still some debate as to whether the frequency weightings given for the z-direction could be applied in their original form. Several studies suggest that assessment of motion in the x- and y-directions may need require their own frequency weightings, as there is a different relationship with frequency and motion sickness severity [21].

The research organisation TNO is actively considering these limitations, and is developing its own motion sickness models, which explicitly takes into account motion sickness effects other than simply emesis and also accounts for motion in all three degrees of freedom (x,y,z). Details about this model are anticipated to be made public in the coming months [22]. Additional information is also presented in Appendix 1 of this report, where TNO use there model to perform additional analysis.

2.3 Motion Sickness Discussion

During engagement with stakeholders, the discussion regarding motion sickness was extensive, with many people having a wide range of opinions. Subsequent analysis of the interviews that were carried out identified a number of themes, which are presented and discussed here. Themes were related to both motion sickness specifically, and other ways in which working on floating offshore wind farms (FOWFs) is expected to be different to the experience of working on fixed wind.

2.3.1 Expected level of motion sickness on FOWFs

When stakeholders were asked about whether they thought that motion sickness would be a challenge for technicians working on FOWFs, not all respondents were aligned. Generally, opinions on this topic were provided by those who had worked on floating structures (including demonstration FOWFs), and those who study motion sickness. Opinions were broadly split along this division, with academics and researchers sure that motion sickness would be a concern, and operators confident that the level of motion would be manageable.

The reason for this split may be due to the limited amount of FOW experience to date. Current demonstrator FOWFs are in generally sheltered locations, and thus do not experience the type of motion that is anticipated for future commercial scale FOWFs. As a result, the fact that individuals who have worked on these structures have not been motion sick (or even noticed the motion in some instances) does not necessarily mean that motion sickness is not a concern for FOW.

Stakeholders were in agreement that motion sickness would depend significantly on the type of foundation used. There was agreement that as a tension leg platform (TLP) moves less than other types, it will induce less motion sickness. As spar buoys have a lower heave response than semi-submersibles, they are likely to also be less provocative of motion sickness. However, one stakeholder who had worked on spars did remark that the rotational yawing motion of the FOWT in some situations was unsettling and led to some minor motion sickness symptoms.

One further element which will affect the degree of motion sickness are the situational factors, such as body position of the technician, the possibility of viewing the horizon, and odours in the location, amongst other things [23]. These elements can all aggravate or alleviate motion sickness, yet are not covered by the current standards, and haven't been quantified experimentally [19]. Anecdotal evidence from those who had worked in the field suggested that odours and air circulation in

particular can have a significant effect on levels of motion sickness, and should be considered accordingly in any environmental design features.

2.3.2 Habituation

A critical factor in the severity of motion sickness is habituation – “getting sea legs.” Almost all stakeholders thought that habituation would have a significant impact on the degree of motion sickness experienced by individuals. However, there is no way to account for the effects of habituation in any of the predictive models introduced above. A brief discussion on habituation, based on both the literature and stakeholder input, can qualitatively explain the phenomenon and its effects in a FOW context.

A person's response to motion sickness changes with time. At first, as the motion sickness dose increases, they become gradually sicker. However, after a certain period of time, the brain learns to anticipate the different combinations of motion signals, and the person adapts – becoming habituated to the signals. The effect is well known amongst sea farers, and has been noted in several case-study type academic pieces [24]. For instance, measurement of motion sickness of crew on a research vessel in the Southern Ocean over several days produced the graph in Figure 3 [25]. The return trip encountered rougher conditions earlier on than the outgoing trip, leading to a greater and earlier peak in motion sickness level. Nevertheless, both the outgoing and return trip observed reduced motion sickness after three days of being at sea, despite encountering rough conditions. This 3-day duration for habituation was repeated by both academic and operational stakeholders, and has also been noted for other motions, such as space sickness [26].

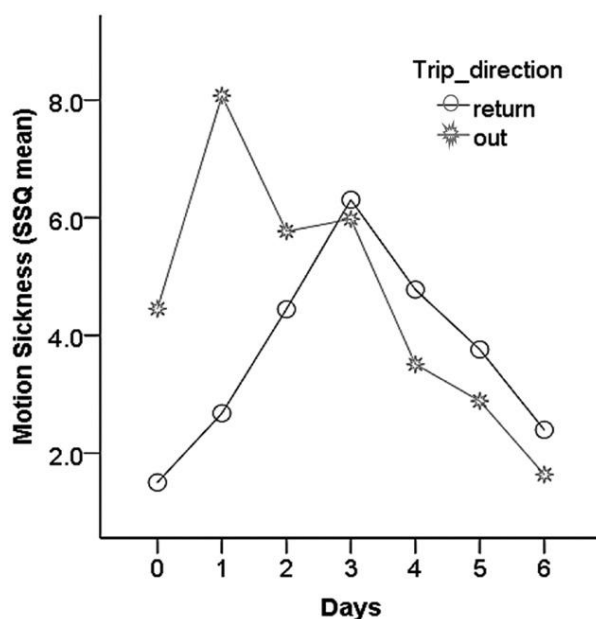


Figure 3: Variation in crew motion sickness levels over two 6-day trips in the Southern Ocean; from [21]

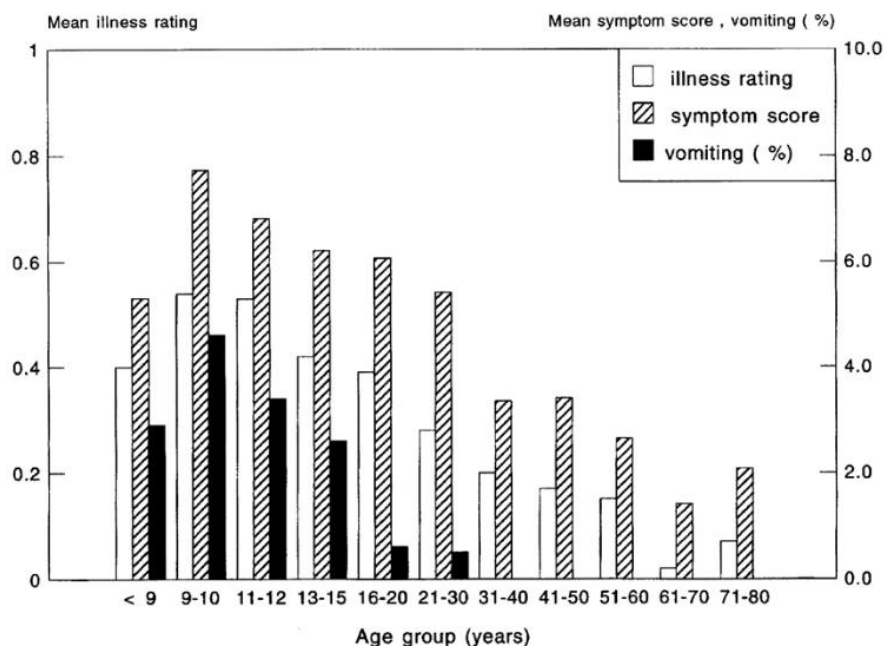
Habituation and de-sensitisation effects can be both short-term (on the scale of days) and long-term (on the scale of years). Short-term, the rate at which someone is habituated to motion depends on how much motion they are exposed to, and if that motion is sustained. For instance, technicians transiting on a crew transfer vessel (CTV) will receive a dose of motion that makes them sick, but won't be in that moving environment for long enough (1-3 hrs) to become habituated to it. They may therefore continue to be sick over a larger number of days, as they won't have the opportunity to adapt to the motion. By contrast, a technician working from a service operations vessel (SOV) will be

on board for 2 weeks. This allows them to habituate to the motion in the first few days, after which they won't be made motion sick by the motion of the vessel.

However, the technicians will only be adapted to that particular motion. If they then move to a different motion environment, they may become sick again. For instance, one stakeholder gave the example of people becoming sick in heavy weather, even though they were habituated to the ships motions in calmer weather. The degree to which habituation to one motion environment protects against a different motion environment depends on the similarity of the motion character. It is therefore not certain whether habituation to the movement of an SOV would protect against motion sickness in a FOWT. There was a range of views on the extent of this protection, but all stakeholders agreed that some protection would be afforded. Most agreed that it would depend on the relative dominance of vertical or horizontal motion for the two environments.

In the longer term, there may be habituation effects where individuals gradually get more adapted to motion with years of experience. Certainly, stakeholders confirmed that most technicians who go to sea regularly do not often get seasick, and a similar effect has been observed in research for space sickness where those who had experienced the motion previously were more habituated to it [27]. However, within that study, it was noted that this may be as a product of self-selection: those who suffered motion sickness during an activity were less likely to repeat it. This is likely to be the case for technicians as well – those who are regularly motion sick are likely to leave the profession, or seek roles which do require long durations exposed to provocative motion.

The reduction in susceptibility with increasing career length is also related to a potential age-related effect. Surveys of over 3,250 passengers undertaking coach journeys indicated that the likelihood of suffering from motion sickness varies with age, as shown in Figure 4 [13]. The authors noted a peak in susceptibility at the age of 9-10, followed by a general reduction with increasing age. This may have an implication for technicians, as many start their work in their early 20s. As they stay in their profession for a number of years, they may become less susceptible regardless of their time at sea.



(Turner & Griffin, 1999)

Figure 4: variation in motion sickness susceptibility with age, from [24]

2.3.3 Effects of motion sickness in the FOW context

Motion sickness has many effects on human operators, beyond just vomiting, even though this is often the focus in discussions of motion sickness as it is an obvious objectively observed symptom. Other symptoms, such as lethargy and nausea, are subjective and as such are far more difficult to measure. Their impact on technicians is no less important, and may in fact be more so as these symptoms are induced at lower motion dose levels, so will be more present in a FOW setting.

Of particular relevance for FOW is the Sopite syndrome. The symptoms of Sopite syndrome are “drowsiness, yawning, disinterest and disinclination to work, lack of participation in group activities, mood changes, sleep disturbances, and mild depression” [5]. Depending on the individual, Sopite syndrome may be the only symptom of motion sickness, making it difficult to identify. The impact that Sopite syndrome can have on a technician's performance is therefore significant. Experiments have shown that those susceptible to Sopite syndrome are less effective at carrying out tasks, and utilising working memory, especially if the task being performed is routine [5]. Additionally, it was suggested that spatial tasks are particularly negatively affected by this syndrome.

As well as impact on the maintenance tasks, the effect of motion sickness should also be considered for the wellbeing of the technician outside of working hours. It is anticipated that the large majority of technicians working on FOWFs will be based on SOVs, living in close quarters with other vessel inhabitants. Therefore, any negative effects of Sopite syndrome on a technician's ability to integrate well with others on the vessel could prove a challenge with long term consequences, as many stakeholders emphasised the need for good onboard relations for the long term effectiveness of SOV access.

Additionally, in a physical context, it has been shown that seafarers have far greater likelihood of injury, both at sea and onshore, than the general population [28]. The exact cause of this is not clear, but stakeholders thought that it was likely due to fatigue, and were aware anecdotally of similar effects for bottom fixed wind.

2.3.4 Medical mitigation measures

Motion sickness medications, in use for over 50 years, are most effective when taken as a preventive measure [1]. They have limited effectiveness after symptoms begin, especially if taken orally due to the symptom of “gastric stasis” (stomach activity stopping). Oral medications should be taken 1-2 hours before the motion, while other methods also need to be administered in advance [23]. There are two types of motion sickness medications: anticholinergics and antihistamines, which are assumed to act on different pathways.

The optimal drug for motion sickness is the anticholinergic Scopolamine, also known as Hyoscine. A review of motion sickness medications found it to be the most effective at reducing motion sickness symptoms and “the drug of choice for individuals who wish to maintain wakefulness during travel” [23] [29]. The drug can be administered via four routes: injection, oral, nasal spray, and transdermal patch. The onset durations for these methods are 15 mins, 30 mins, 30 mins and 6-8 hours respectively. While the transdermal application requires a longer onset period, it remains effective for 72 hours. In contrast, the other methods only provide protection for four hours [1] [23].

The most common side effects for Scopolamine are dry mouth, dry eyes, blurred vision, and photosensitivity [30]. The drug can also induce drowsiness. For this reason, in military applications it is combined with Dexamphetamine – a stimulant with effectiveness at treating motion sickness - leading to a powerful medication with the respective side effects of sedation and stimulation

cancelling each other out. However, due to the potential for drug abuse, this combination is not available outside of specialised military applications [1].

Other medications shown to be effective in the prevention and treatment of motion sickness are first generation antihistamines [23]. They have a longer effective duration of action than Scopolamine when administered orally (8 hours versus 4), but require a longer onset duration (typically 2 hours). These antihistamines are well known to cause drowsiness and sedation, while non-sedating antihistamines are generally not effective at combating motion sickness [31]. As a result, antihistamine-based medications may be less effective in a FOW setting.

2.4 Additional Human factors considerations

The moving environment may present challenges for technicians in addition to the possibility of motion sickness. Furthermore, FOWFs may experience novel operations and maintenance (O&M) challenges due to their further-from-shore location compared to current bottom fixed projects, and the harsher environment experienced at these locations.

2.4.1 Impact of motion on Technician Energy and Components

It is well documented in the literature that performing tasks in a moving environment requires much greater energy than performing a similar task in a stationary environment [24]. This is backed up by anecdotal evidence, in which operators on CTVs have noted that remaining upright on a moving vessel is exhausting. The moving environment of a nacelle may therefore increase the energy expenditure of the technicians, increasing their fatigue. Movement may also make some tasks challenging, in particular those which require rope access such as blade repair, as the blades will be moving with much greater amplitude than those on a fixed bottom wind turbine.

The motion of the turbine could also impact the components in the turbine tower and nacelle. The additional motion imparted by the waves, and the small, periodic motion could lead to a reduced fatigue life, and quicker progression through the fatigue life. This could have two implications for the technician. First, the service lifts that they use to move up and down the tower may break more often. This would lead to more climbs required, fatiguing the technicians. This is a particular concern as turbine capacity, and therefore tower size, increase.

Second, components around the turbine may break more quickly, so more jobs will be required on a turbine, adding to technician workload. Stakeholders thought that this issue would be compounded, as operators would be unlikely to run a FOWT if there was any concern that a component was degrading. This contrasts with fixed wind as the costs of component replacement within fixed wind is significantly cheaper than floating due to challenges with major component replacement for FOW.

There may also be a challenge when considering the lifting operations on the turbine itself. Technicians are very reliant on cranes both at the transition piece if using CTV transfer, and from the nacelle regardless of transfer method. If the nacelle is moving over a much greater range on floating than on fixed this may compromise the ability of the technicians to perform the transition piece to the nacelle lift, due to safety concerns as the lifting will be performed in a dynamic environment. This would have significant challenges for the performance of maintenance as technicians are very reliant on cranes to carry out their work. Some respondents felt that this could be overcome by novel methods such as drone delivery. However, the feasibility of these methods is yet to be proven.

2.4.2 Locational challenges of FOW

The location of future FOW farms may also affect the day-to-day experience of the technicians. The deeper water and far-from-shore locations are likely to mean rougher overall sea conditions. This will mean that not only will the turbine move more energetically, but the SOV, where technicians are housed, will also move more, potentially inducing motion sickness onboard, and leading to fatigue. Several stakeholders felt that this would be a challenge particularly for technicians as compared to other seafarers as they are not used to such an environment, particularly at the outset of their career.

Energetic SOV motion may be particularly prevalent if the wind farms are placed in locations outside of the North Sea, such as the Celtic sea or Northern Scotland. Some stakeholders expressed a view that the wave environment in these locations would be significantly different, and may lead to unexpected vessel responses if those locations weren't considered in the vessel design process.

The distance from shore may also affect technician's wellbeing. It has been suggested that if FOW farms are located significant distances from shore, then there may be a change of working patterns, so that technicians move from a two week-on, two week-off pattern to a three week-on, three week-off pattern. However, it was widely thought by stakeholders that this would have negative effects on technician wellbeing. Research has suggested that offshore workers feel increasing amounts of fatigue over a two-week period, with a "dip" in energy levels noted around day 10 offshore [32].

Sleep also seems to degrade with time offshore, compounding this problem [33]. Increased fatigue is known to affect safety related tasks, therefore moving to a 3-week rotation is likely to have negative implications for technicians' health in the long and short term, and should be avoided. Stakeholders mentioned that even for operations performed from a shore base, operators have in the past moved from a 3 to 2-week rotation to reduce fatigue.

3 ORCAFLEX MODELLING OF TURBINE MOTION

In the previous section, the reviewed literature and stakeholder engagement suggested that motion sickness may be an issue for technicians working FOWTS, but that there was little consensus around the scale of the problem. A quantitative assessment can be made using numerical modelling techniques. Therefore, in this section the motion of a nacelle is modelled, and the motion data assessed to estimate the likelihood of motion sickness which it would result in.

3.1 Methodology

To estimate the motion character of a FOWT nacelle and the likelihood of motion sickness, the FOWT is modelled in the simulation software OrcaFlex [34]. Three turbine models were simulated: a 10 MW BOWT, a 15 MW semisubmersible FOWT, and a 15 MW TLP FOWT. The BOWT and the semisubmersible designs are validated models available from the OrcaFlex software provider Orcina [35]. Each turbine was considered in three operating conditions:

- (a) **Turbine rotor idling:** the rotor is left to freely rotate while the blades are feathered at 90° into the wind.
- (b) **Turbine generating:** the turbine is in operational mode, and is producing electricity. The blades automatically pitch to ensure the correct torque is applied to the generator. The blade pitch is controlled by an external pitch controller provided by Orcina.

- (c) Turbine parked, yawed out of the wind:** the turbine rotor is parked so that one blade is in a horizontal position. The nacelle of the turbine is then yawed out of the wind, so that the plane of the turbine blades is in line with the wind direction. The horizontal blade is directed into the wind direction and the blades are feathered at 90°.

For all simulations, a common reference system is used. This ensures that the simulation results can be interpreted and compared accurately. The orientation of the X,Y and Z directions are presented in Table 6.

Table 6: Orientation of the X,Y,Z directions in the OrcaFlex models.

Direction	Interpretation in model
X	Horizontal direction, in line with wind and waves
Y	Horizontal direction, perpendicular to wind and waves
Z	Vertical direction, aligned with gravity

Upon completing the modelling, the motion time history results are post-processed to determine the likelihood of motion sickness. This analysis will provide insights into the type of motion experienced at the nacelle. The different foundation designs are next described, along with the load cases considered in the simulations.

3.1.1 Load Cases

The environmental conditions used in the modelling are chosen to represent the conditions which are expected when a technician will be in the nacelle. The wave peak period (T_p) and average wind speed (U_w) used in the simulations were derived from an analysis of the average metocean conditions at three locations around the UK representative of future FOWF sites. The average wind speed considered for different wave H_s and T_p pairs is shown in Table 7.

Table 7: 1-hour mean wind speeds in m/s at 100m above mean sea level for each H_s - T_p pair

		T_p [s]					
		4	6	8	10	12	14
H_s [m]	0.5	8	8	6	6	6	6
	1	12	10	8	8	8	8
	1.5		14	12	10	10	10
	2		16	16	12	12	12
	2.5		16	16	14	14	14

3.1.2 Post-processing: Application of standards and guidance

The theory of motion sickness presented previously suggests that the degree of sickness is related to the magnitude and frequency of environmental acceleration. Therefore, the results will focus on the acceleration of the nacelle, initially summarised by the RMS of the recorded acceleration. The NORDFORSK and ISO 2631-1 standards are then applied to the recorded acceleration data to estimate the effects of the simulation motion. Colour coding is used to denote the different motion limits from the NORDFORSK guidance, Table 8.

Table 8: Colour-coded NORDFORSK limits [12], $g = 8.91\text{m/s}^2$ (acceleration due to Gravity)

Task	Vertical Acceleration (RMS)	Lateral Acceleration (RMS)	Roll (RMS)
Light manual work	0.2g	0.1g	6.0°
Heavy manual work	0.15g	0.07g	4.0°
Intellectual work	0.10g	0.05g	3.0°
Transit passengers	0.05g	0.04g	2.5°
Cruise Liner	0.02g	0.03g	2.0°

As an alternative to Equation 1, the MSDV for a long period can be estimated from a shorter sample by taking the RMS of the sample's weighted acceleration time signal, and multiplying it by the square root of the longer period [17]:

$$MSDV = A_{W_{RMS}} \times T^{\frac{1}{2}} \quad (3)$$

The frequency weighting operation is performed using the *VibrationData* toolbox available from EndaQ [47]. Equation 3 is applied to estimate MSDV over a three hour period from the 30 minute sample. As per equation 2, the MSI can then be calculated by multiplying the MSDV by 1/3. As highlighted in the previous discussion of the ISO standard, the frequency weighting has been formulated for acceleration in the vertical direction. However, in the absence of more appropriate guidance, the same frequency weighting will be used for acceleration in the horizontal direction.

3.2 Results

3.2.1 Bottom Fixed foundation

As anticipated for a BOWT, the nacelle's motion results indicate negligible displacement in the heave direction. However, there is significant horizontal acceleration attributed to the bending of the wind turbine tower. The maximum RMS values for the bottom fixed foundation across all simulations are shown in Table 9. The values for roll motion and acceleration in the Z-axis are below those stated in the NORDFORSK guidance for all tasks. The maximum RMS acceleration in the lateral direction of X does exceed the limit for intellectual work in the idling configuration. Additionally, the horizontal acceleration exceeds the transit passenger limit in the generating conditions, and the cruise liner limit in the parked configuration.

Table 9: Maximum RMS values (in g) for fixed foundation, exceeded NORDFORSK limit denoted by colours in Table 9.

	Generating	Rotor Idling	Rotor Parked
Roll	0.009	0.001	0.033
X	0.049	0.06	0.032
Y	0.018	0.003	0.004
Z	0.001	0.002	0

The estimated MSI derived from motion in the X direction is calculated across all simulations, shown in Figure 5. The largest MSI values occur at those simulations with the largest RMS of acceleration – at low T_p , with the maximum at T_p of 4s and H_s of 1m. In this configuration, the estimated proportion of a “standard” population who would start to vomit is 13.7%.

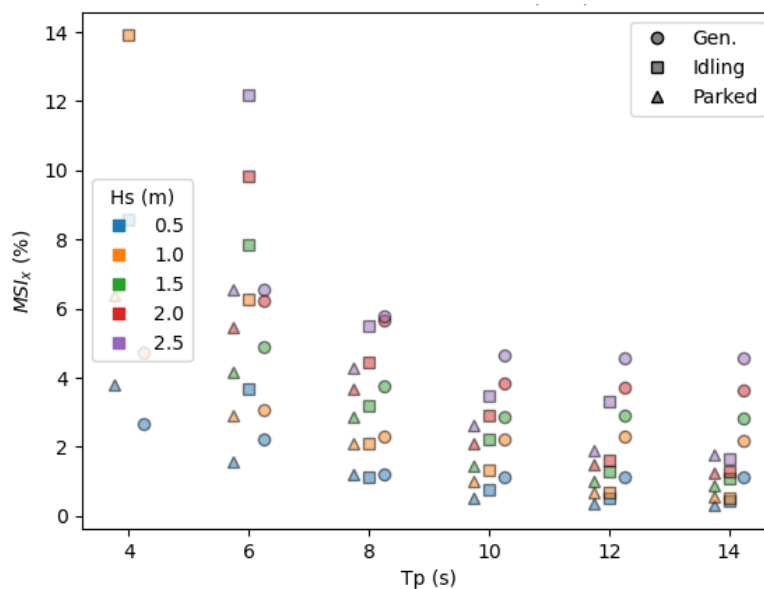


Figure 5: Estimated MSI from motion in the X direction for a BOWT

3.2.2 Semisubmersible foundation

The simulations involving the semisubmersible foundation exhibit limited variation in acceleration across the three operational scenarios, with only a slight increase in acceleration observed in the generating cases. Table 10 presents the maximum RMS values of acceleration across all simulations. The maximum RMS of the X direction acceleration is greatest in the generating cases and consistent across the idling and parked cases. Additionally, there is negligible movement in the Y direction and low RMS acceleration in the Z direction.

Table 10: Maximum RMS values (in g) for semisubmersible

	Generating	Rotor Idling	Rotor Parked
Roll	0.027	0.003	0.181
X	0.031	0.02	0.02
Y	0.007	0	0.001
Z	0.008	0.008	0.008

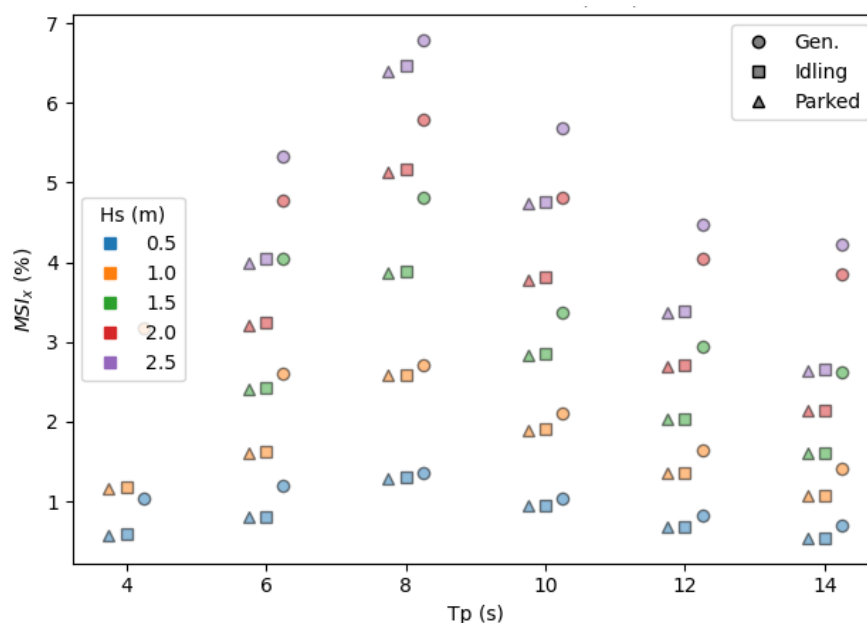


Figure 6: Estimated MSI for X direction for semisubmersible

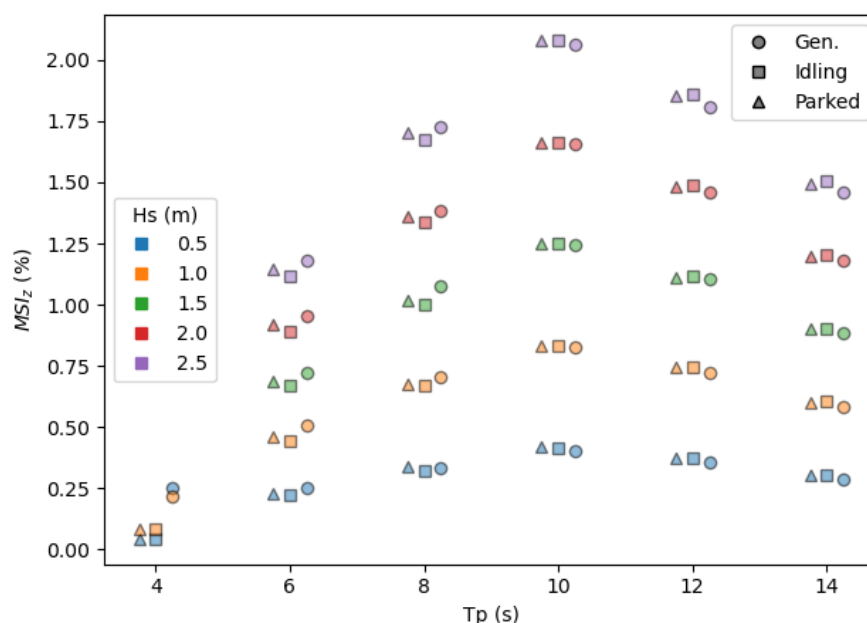


Figure 7: Estimated MSI for Z direction for semisubmersible

The calculated MSI estimates for X-acceleration for the simulations are provided in Figure 6. The maximum expected prevalence of vomiting is 6.8% , occurring when the H_s and T_p have values of 2.5m and 8s respectively. There is a generally increasing prevalence of motion sickness with increasing H_s (and wind speed).

A modest maximum MSI of 2.1% is estimated from the acceleration results in the Z direction, as shown in Figure 7. This lower MSI value is attributed to the comparatively smaller acceleration power in the Z direction relative to the X direction. The peak MSI is observed at a slightly higher T_p of 10s, suggesting that the frequency response in the Z direction occurring at a lower frequency than the X direction response.

3.2.3 TLP foundation

The horizontal acceleration of the nacelle on the TLP foundation also differs according to the operational state of the turbine. Table 8 presents the maximum RMS values for acceleration across all simulations. The maximum RMS of the nacelle in the operational condition at 0.31g is equal to that of the semisubmersible foundation, however, there is a significant reduction of 66% in the RMS of acceleration when the turbine is in the parked or idling configuration.

Table 11: Maximum RMS values (in g) for TLP simulations

	Generating	Rotor Idling	Rotor Parked
Roll	0.007	0.001	0.028
X	0.031	0.009	0.01
Y	0.005	0	0.004
Z	0.001	0	0

The distinct acceleration profiles corresponding to various operating conditions result in differing MSI estimates, as illustrated in Figure 8 for X-acceleration. The MSI estimates reach approximately 10.7% in certain power-generating scenarios. Conversely, in non-generating scenarios, the MSI values are significantly lower, with a maximum estimate of 3.1% in the idling condition. For the acceleration in the Z direction, the projected MSI values are minimal, with a peak estimate of 0.37%.

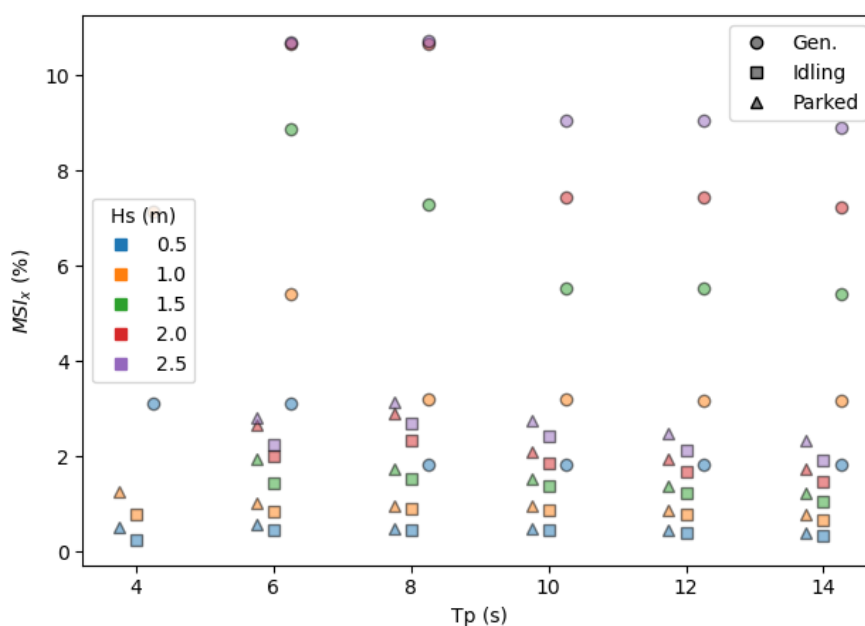


Figure 8: MSI from the acceleration in the X direction for the TLP FOWT

3.3 Discussion

All foundations analysed in this study exhibit a degree of acceleration at the nacelle. The predominant direction of acceleration for all three foundation types is in the X direction, corresponding with the wind and wave forces acting on the FOWT. The RMS of the accelerations from all simulations indicate that the magnitude experienced in the nacelle is generally low and consistent across the three technologies. A summary of the maximum RMS and MSI in the X direction

is shown in Table 12. Notably the largest RMS and MSI values occur for the idling BOWT case, with the parked BOWT case also displaying significant acceleration and MSI estimates.

Table 12: Comparison of maximum RMS and MSI values in the X-direction across all foundations

	BOWT RMS (g)	Semisub RMS (g)	TLP RMS (g)	BOWT MSI (% vomiting)	Semisub MSI (% vomiting)	TLP MSI (% vomiting)
Generating	0.049	0.031	0.031	9.9	6.8	10.7
Idling	0.060	0.020	0.009	16.8	6.5	2.7
Parked	0.032	0.020	0.010	7.8	6.4	3.1

Such a result suggests that motion in the nacelle of FOWTs will be less impactful than it already is for bottom fixed turbines, and may therefore not be a significant concern. However, it should be noted that the cases which lead to the high BOWT results are for very short wave periods of 4-6s. Such steep waves (and therefore these large accelerations) are quite rare.

Comparison of the two floating foundation types suggests that in the parked and idling configurations, the TLP moves significantly less than the semisubmersible, resulting in around 50% lower MSI and RMS results. As technicians are most likely to be in the nacelle under these operational conditions, the TLP therefore presents a better work environment for technicians. As an example, Figure 9 presents a comparison of the derived MSI for the TLP and the semisubmersible in Hs of 2.5m. At all Tp values considered, the MSI is less for the TLP.

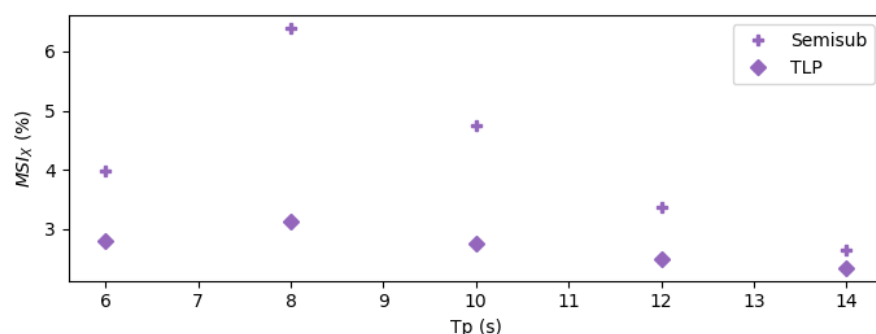


Figure 9: Comparison of MSI in the X direction for parked TLP vs semisubmersible foundations at Hs of 2.5m.

In general, the results indicate that for operational cases where a technician is likely to be in the nacelle, the TLP provides a more stable and less provocative working environment than the semisubmersible foundation. The degree to which this result can be generalised to all semisubmersible and TLPs is not certain from this analysis. Fundamentally, it is likely that TLP designs will lead to less dynamic nacelles, as they are constrained in heave and pitch, which are the motions that lead to the biggest nacelle acceleration. However, while all semisubmersible foundations are not constrained in this way, the extent of these motions will depend on the individual designs. In particular, designs which limit heave and pitch, such as those with heave plates, are likely to have less motion, and therefore provide a better environment for technicians.

Additionally, there are qualifications to the interpretation of the motion sickness estimate that should be considered in this analysis. Firstly, the standard has been applied in a manner it was not intended for. ISO 2631-1 only considers vertical motion, with the frequency weighting factor based on experiments considering acceleration in this direction [17]. It has been applied here due to the absence of similar guidance for horizontal motion, but the implicit assumption – that vertical motion is as provocative as horizontal motion and has the same frequency relationship – has not been

verified. Literature suggests that horizontal motion may be twice as provocative as vertical motion. If this is the case, the percentage of the population experiencing vomiting due to nacelle motion may be closer to 15%. Additionally, the ISO standard only considers vomiting, which is the final stage in a series of progressively debilitating motion sickness symptoms. Motion sickness may impair a technician's ability to work at lesser symptoms than the vomiting captured by the standard, as they occur at lower a MSDV than vomiting.

4 CURRENT TECHNICIAN EXPERIENCE

In addition to the modelling performed above, insight into the risk of motion sickness can be achieved by exploring its effects on current operational FOWFs. At present, there are two operational FOW demonstration projects in the UK: the Kincardine project, owned by Kincardine Offshore Wind Limited, and serviced by MHI Vestas; and the Hywind Scotland project, owned by Equinor and serviced by Siemens Gamesa. The experience of workers on these farms was investigated using a qualitative research approach.

4.1 Kincardine Perspective

The Kincardine FOW demonstration project, located off the coast of Aberdeen, features five turbines. The turbines are corner mounted on the three column *Windfloat* foundation by Principle Power. Maintenance and repair work within the nacelle is performed by two teams of MHI Vestas technicians, each working in two-week shifts. We interviewed three technicians involved with the project. Each has a unique role at Kincardine and previous offshore experience, either in the oil and gas (O&G) sector or fixed offshore wind.

Generally, when technicians experienced motion sickness at the site, the motion of the CTV, rather than the foundation, was the cause. Technicians found that transit in long-period swells was particularly provocative of motion sickness, especially when transiting in the dark. The longer technicians experienced this motion, the worse the symptoms became. One technician, who had spent several hours in this environment, stated that they were incapacitated for the entire day following the provocative motion. In general, these types of failed transfer, where technicians were subject to especially provocative motion and unable to transfer were noted to have a poor effect on morale.

After transfer from the CTV, the FOWT is considered 'surprisingly stable,' even by visitors. The substructure of the turbine often serves as a recovery spot from motion sickness induced during transit. By the time the work briefing, which lasts 45-60 minutes, is completed, all motion sickness symptoms typically dissipate. The symptoms do not return once the technicians reach the nacelle, as the level of motion is comparable with fixed offshore wind. The stability of the FOWT was attributed by the interviewees to the design of the foundation, in particular its incorporation of heave plates.

For team members and visitors prone to motion sickness, the most common method of alleviation is anti-nausea medication. The drowsy side effects do not seem to have a significant detrimental impact in this setting. Additionally, motion habituation was observed. For instance, one colleague who regularly experienced motion sickness at the beginning of their two-week shift became accustomed to it after a day or two of transiting. This habituation appeared to be present across all technicians on site, as there was an observable increase in motion sickness on return from prolonged time away.

4.2 Hywind Scotland Perspectives

Hywind Scotland is a FOW project, located off Aberdeenshire coast from Peterhead. The project consists of five 6 MW turbines mounted on spar platforms. The turbines are supplied by Siemens Gamesa, and serviced by the company.

Unfortunately, despite repeated efforts and several approaches, it was not possible to engage directly with the current technicians at the site. However, two sources provided information on working conditions at the Hywind Scotland wind farm.

The first source, referred to as Technician A, was a Siemens Gamesa technician who had not worked directly on the FOWT but had friends and colleagues who had. The second source, referred to as Technician B, was a high voltage technician for Siemens Energy. Technician B had worked on the high voltage (HV) equipment at the Hywind site several years ago during the beginning of the farm's operation. On the Hywind turbines, this equipment was located near the nacelle, so the technician experienced the similar motion to that in the nacelle.

Both sources indicated that motion was definitely felt at the nacelle of the FOWT. Technician A heard many people negatively compare the motion to that of a boat. Technician B confirmed considerable motion in the tower where they worked, mainly driven by the pitching of the structure, particularly in gusts. This technician also worked in the tower while the turbine was both generating and idling, noting a significant difference in platform pitch. Pictures shared by the technician showed that in the generating condition, the tower was pitched several degrees from the vertical in the downwind direction, while in the idling condition, the tower pitched by a similar angle into the wind.

Both technicians were aware of those working in the nacelle taking mitigating actions to reduce the effects of motion sickness. Technicians A and B had heard of people susceptible to motion sickness taking the common medication *Kwells* before beginning their work, which they believed to be effective. Additionally, Technician B had observed technicians needing to move to the heli-hoist area on top of the nacelle to look at the horizon to alleviate the feelings of motion sickness induced by the movement of the nacelle. This appeared to be effective but required technicians to take time from their shift.

4.3 Discussion

The results of the discussions with the FOW technicians do not present a consistent view of the risk of motion sickness on FOWTs. In particular, technicians from Kincardine did not report any instances of motion sickness, whereas those from Hywind did. This suggests that while motion sickness should be a consideration for those planning FOWF, it is not ubiquitous and may depend on specific project conditions. Factors such as the type of foundation design and the conditions under which technicians can access the turbines seem to play a significant role.

Exploring further the difference between the two farms, the foundation design appears to have a notable effect on the motion of the nacelle. The spar design at Hywind was reported to cause significant movement in gusty conditions, indicating that the system is relatively soft in pitch and responsive to wind speed variations. In contrast, Kincardine's design, which includes heave plates, was cited as being very stable. The added mass (inertia) from the heave plates likely makes the system less reactive to changes in environmental loading, reducing the risk of motion sickness.

The operating condition of the nacelle also seems to impact technician experiences. Kincardine technicians are only permitted to access the turbines in non-operational conditions, whereas a Hywind HV technician reported being in the tower while the turbine was generating. This operational

scenario could lead to increased movement, as suggested by Section 3, and indicates that the effect of operating conditions on human performance should be considered in maintenance design decisions.

In provocative environments, the impact of motion sickness on human operators appears to be mixed and difficult to quantify. Both sets of stakeholders reported that technicians took motion sickness medication. However, it is unclear whether the motion and/or medication directly affected their ability to perform their jobs. The fact that some individuals chose to take the medication may indicate they felt it was necessary to work effectively, but it could also be that the motion would not have impacted them even without the medication.

Additionally, it is challenging to assess the extent to which motion sickness affected them, even with medication. Evaluating the technician's level of motion sickness and the impact on performance is difficult through anecdotal and secondary information. The only concrete example of motion sickness affecting a technician's ability to work was the reported incident where a technician needed to leave the nacelle to recover. However, this account is anecdotal, with no indication of the frequency of such events or the environmental conditions that necessitated the pause from work.

The applicability of these findings must be considered in light of the limits of the responses received. Kincardine respondents were only ever on the platforms in significant wave heights up to 1.5m Hs, so their experiences of limited motion may not persist in higher sea states. Hywind data was partly secondary and from a technician who had not worked on-site for several years, potentially affecting the information accuracy. Additionally, the SOV information was provided by managers, who may have an incentive in claiming a contented workforce. However, the facilities were verified firsthand.

5 REVIEW OF APPROACHES TO LAB TEST MOTION

As noted in the review section above, research on motion sickness to date has focussed primarily on sea sickness caused by the motion of vessels on the sea surface, with additional research also considering the motion of aircraft. Vessels and aircraft are unlikely to present a similar moving environment to FOWT nacelles, and additional lab research may therefore be required to develop an empirical understanding of motion sickness in these types of motion environments.

Broadly, laboratory research into motion sickness involves the use of a motion simulator to create a controlled moving environment, placing a human subject in the simulator for length of time, and assessing the participant both before and after the experience. In this section, a review is provided of the requirements in setting up this type of empirical, lab-based, research on human participants. Information is also provided on the types of testing which may be most appropriate to test the effects of motion on technicians' performance and wellbeing.

5.1 Participant Welfare

Testing the effects of motion on human operators inherently involves participants experiencing mild discomfort. Therefore, participant safety and protection must be prioritised throughout the study. This section will review the oversight and ethics standards relevant to human testing, considerations for participant selection, participant protection measures, and incentives for participation.

5.1.1 Oversight and Ethics Boards

The World Medical Association (WMA) has outlined ethical considerations for human research in the Declaration of Helsinki [34]. This details the “ethical principles for medical research involving human participants.” Some key principles relevant to testing motion sickness include:

- Engagement with communities impacted by the research (in this study, that would include technicians and offshore workers);
- The researchers are responsible for protecting the well-being, confidentiality, and autonomy of personal information. Information, when possible, should be anonymised; and
- Research should be done in a method that minimises harm to participants and the environment.

In addition to following ethical standards, any testing is expected to fall under the oversight of an ethics board, which ensure proper safety procedures are in place. The ethics board should be local to where the study is conducted, and members should be familiar with the community engaged as participants. Once a research methodology has been proposed, it should then be submitted to the ethics board for approval and guidance.

5.1.2 Participant Selection

Before requesting participation, studies should determine a desired sample size based on research budget and timeframe. The sample size should be large enough to control for known characteristics affecting motion sickness, such as age and gender. When determining sample size and considerations, the WMA reminds that “groups that are underrepresented in medical research should be provided appropriate access to participation in research” [34]. However, in this instance, due to time and space constraints, as well as difficulties in finding participants, this may not be possible.

For female participants, stakeholder engagement has suggested limiting participation to those on birth control, and carrying out the study at the same point in the participant's menstrual cycle, neither during menstruation or ovulation, as those are the points of highest and lowest motion sickness susceptibility respectively [35].

Potential participants should be screened to remove individuals with long-term conditions or predispositions, including those with past head injuries, chronic headaches or vertigo for participant safety. Participants should also complete a questionnaire such as the Motion Sickness Susceptibility Questionnaire (MSSQ) to determine their potential response to the selected motions.

Prior to the experiment, participants should be surveyed for classification and self-diagnosis. Personal information, such as age, gender, sex, and susceptibility, should be recorded and associated with an assigned number or letter to ensure anonymity after the tests. This allows for grouping during analysis to better understand how characteristics such as age may affect motion sickness.

5.1.3 Participant Protections and Incentives

Prior to the research, each participant should be made fully aware of the potential risks of partaking in the experiment. They should also consent to the experimental procedure, the time required from them and any planned testing. They should also be made aware that they can stop the experiment at any point in time without repercussions.

In addition to these, participants should be compensated for participating in the study. Incentives should be determined based on standard practices, accounting for the duration of the test and typically taking the form of a voucher at a value just below the minimum wage. A researcher engaged as part of the review who was performing similar research offered a voucher of £12 if a participant attended a 1-hour session, followed by a £24 if they then returned for subsequent testing.

5.2 Motion Replication

Assessing motion sickness for FOW requires an apparatus that mimics nacelle movement across all 6 degrees of freedom (DoFs). As well as the motion limits of a simulator, aspects such as cost, spatial requirements and participant welfare should be considered when selecting an apparatus for experimental design. The requirements of the motion simulator can be determined from the previously presented modelling work.

5.2.1 Simulated Nacelle Motion

In the simulations performed in Section 3, the greatest movement of the nacelle was recorded for the semisubmersible FOWT, at a H_s of 2.5m, and a T_p of 8s. The extent of the motion in the 6 DoFs, presented in Table 13, can provide an indication of the range of motion required from the different motion simulators. The majority of nacelle motion is in the surge direction, with a small amount of heave motion. Additionally, there is a small amount of pitch but little-to-no rotation in both roll and yaw directions.

Table 13: Simulated Nacelle Motion Limits at 2.5 m H_s and 8s T_p

Motion	Min	Max
Surge (m)	-2.32	2.57
Sway (m)	-0.10	0.09
Heave (m)	-0.35	0.39
Surge vel. (m/s)	-0.87	0.83
Sway vel. (m/s)	-0.01	0.01
Heave vel. (m/s)	-0.25	0.23
Surge accel. (m/s ²)	-0.69	0.52
Sway accel. (m/s ²)	-0.01	0.01
Heave accel. (m/s ²)	-0.17	0.17
Roll (°)	0.00	0.06
Pitch (°)	-2.16	-0.31
Yaw (°)	-0.04	0.04

5.2.2 Apparatus Setup and Health and Safety

Health and safety are paramount when testing on human subjects. For any motion simulator used, the testing area should include the apparatus, an egress/ingress system for at least two people, and a recovery space. The access point should have handrails and be wide enough for both the test subject and a team member. The apparatus should secure the test subject with a frame, chair, or harness to prevent falls. Subjects must have access to an emergency stop signal to cease motion and allow egress without negative consequences.

5.2.3 Review of Motion Simulators

A number of potential motion simulator systems have been identified which could be suitable for lab-testing of FOW motion sickness. A brief review is here presented of these simulators, including a comparison of their range of motion with those stipulated in Table 13.

5.2.3.1 Stewart Platform or Hexapod

A Stewart platform, or Hexapod, is mounted on six linear actuators that move it in all six DoF. The platform can therefore trace any movement, provided that it is within the range of the actuators. Historically used in flight simulators for pilot training, the platform has also been used to test motion sickness [50]. The platform can support a sizeable superstructure, meaning that a large variety of testing setups can be created. For instance, a replica nacelle could be mounted on the platform, creating a realistic test for technicians. Two platforms were identified through stakeholder engagement: one at ORE Catapult's Floating Offshore Wind Innovation Centre (FLOWIC) facility and another at the University of Southampton.

5.2.3.2 Cybermotion Simulator

Within the literature, previous studies have used the Germany-based Max Planck Institute's CyberMotion Simulator to analyse motion sickness [37]. This apparatus is 6-axis robotic arm with an enclosed chair attached to one end. The arm is set on a 10m long track to allow for increased linear motion. The enclosed participant area contains audio visual equipment, which the participant can interact with.

Previous work has used this apparatus to assess human perception of motion and motion sickness sensitivity in response to changing frequency of motion [38]. The setup in that work could be mimicked in this instance to recreate nacelle motion, with the previous safety practices providing a framework to ensure participant safety and well-being.

5.2.3.3 Cable Robot Simulator

The Max-Planck Institute's Cable Robot Simulator is a motion simulator that moves in 6 DoF, similar to hexapod designs, but relies on a complex pulley system rather than actuators. The benefits of this apparatus include increased energy-efficiency compared to hexapods, high control levels, and high acceleration capabilities [39]. The apparatus is already equipped with a safety chair to secure in participants, and has been paired with virtual reality (VR) equipment to allow for potential monitoring or testing while undergoing motion. In a previous study, this apparatus has been used to investigate the effects of horizontal fore-aft (surge) motion [38], suggesting that it could be an effective simulator for modelling FOWT nacelle motion.

5.2.3.4 DESDEMONA Motion Platform

The Desdemona motion platform, operated by TNO and located in the Netherlands, uses a centrifugal design which provides motion in all directions except for sway. The apparatus is able to reach a centrifugal acceleration up to 3.3 G [41]. The apparatus is often used as a flight simulator and training tool, participants are strapped into an enclosed box with a screen to allow for visualisation of motion.

This apparatus benefits from established use and safety procedures. However, it focuses on rotational motion. While it can induce and test motion sickness, it is limited to 2 degrees of linear motion. Nonetheless, as the calculated nacelle sway motion is small, this limitation should not significantly impact experimentation. Additionally, it is possible by counterrotating the gimbals to replicate the translational sway motion, provided all linear motion is limited to 4 m[43].

5.2.3.5 3 Degree of Freedom Apparatuses

3 DoF motion are used as flight and driving simulators, as well as in entertainment. The DoFs that these apparatus can move in are heave, pitch and roll [44]. 3 DoF apparatuses have been used to study the effects of mild motion sickness on multitasking capabilities [46] and because of the apparatus's ability to induce sinusoidal-like motion, has been effective in testing the effects of motion on humans. However, 3 DoF simulators wouldn't be able to replicate nacelle motion as accurately or realistically because of the limitations of linear motion, as well as generally having a lower range of motion compared to the other apparatuses presented.

5.2.3.6 Limousine Facility

The Limousine facility at TNO is a single DoF apparatus, which makes use of a sled on a 35m track. A cabin is mounted on the sled, within which is a strapped chair and audio visual equipment. The sled is able to reach velocities of up to 14m/s and acceleration of 5m/s^2 . The apparatus is well suited for sinusoidal motion. The limited DoF of the facility means that only the surge motion can be replicated in this apparatus. However, it is significantly cheaper to use than other, higher DoF, motion simulators.

5.2.4 Apparatus Comparison

Each apparatus's ability to replicate the motions provided by the calculated nacelle movement in Section 5.2.1 are shown in Table 14, where green indicates that the motion requirements are met, and red that they are not. Where information was not available, the space was left empty.

As mentioned earlier, the simulator should be especially capable in surge, heave and pitch motions. With this in mind, the Cybermotion Simulator and Robot Simulator meet all motion requirements, with Desdemona able to simulate the most significant motion laid out in Section 5.2.1. While the Hexapod can move in all six DoFs, it is limited in range in the heave direction and so cannot move the entire extent required. The Limousine facility can fully recreate the surge motion, but cannot move in any other DoF. The SLINE 3 DoF motion simulator is only able to match roll and pitch requirements.

As well as motion limits, two additional key aspects to consider are cost and ease of use. Hexapods and 3 DoF apparatuses are generally more affordable due to their smaller size and wider availability, and could be used by a single organisation such as the Catapult. The Cable Robot Simulator, Cybermotion Simulator, and Desdemona apparatuses are significantly larger and typically operated by specific companies or universities, necessitating collaboration and contractual arrangement to use these spaces. However, these larger apparatuses come with the advantage of being thoroughly tested and fully equipped to handle the desired motions, with testing procedures, insurance and other policies already in place.

Table 14: Comparison of Apparatus Motion Capabilities

Motion Type	FLOWIC Hexapod	Cybermotion Simulator	Cable Robot Simulator	Desdemona	Limousine	SLINE 3DoF
Surge (m)						
Sway (m)						
Heave (m)						
Surge vel. (m/s)						
Sway vel. (m/s)						
Heave vel. (m/s)						
Surge accel. (m/s ²)						
Sway accel. (m/s ²)						
Heave accel. (m/s ²)						
Roll (°)						
Pitch (°)						
Yaw (°)						

5.3 Data Collection

A brief review is next presented of tests which assess different aspects of motion-induced effects on participants, including descriptions of the skills being tested and how to establish a baseline of ability. While several examples are provided for each, it is not advised to do all tests, as that would be extensively time consuming and potentially tiring for the participants.

5.3.1 Dexterity

Fine motor skills can be assessed using pegboards, as shown Figure 10. Commonly employed in occupational therapy for adults [48] and in motion sickness research, a pegboard features a series of holes into which participants place pegs or small pieces, with the task timed to evaluate hand-eye coordination [48]. This method provides a straightforward way to assess fine motor skills.

A simple test is the nine-hole pegboard in which the participant is required to place nine pegs into holes as quickly as possible with their dominant hand. The simplicity of the nine-hole pegboard allows for a quick and standard test. In the Purdue test board, both hands are tested simultaneously, and the participant is required to place a set combination of pins, washers and collars into each hole. Different combinations of washers and collars allows for variation in the complexity and demand of the test. As both pegboards contain small and unsecured pieces, it is recommended that this type of test is not performed inside the motion simulator while in motion.

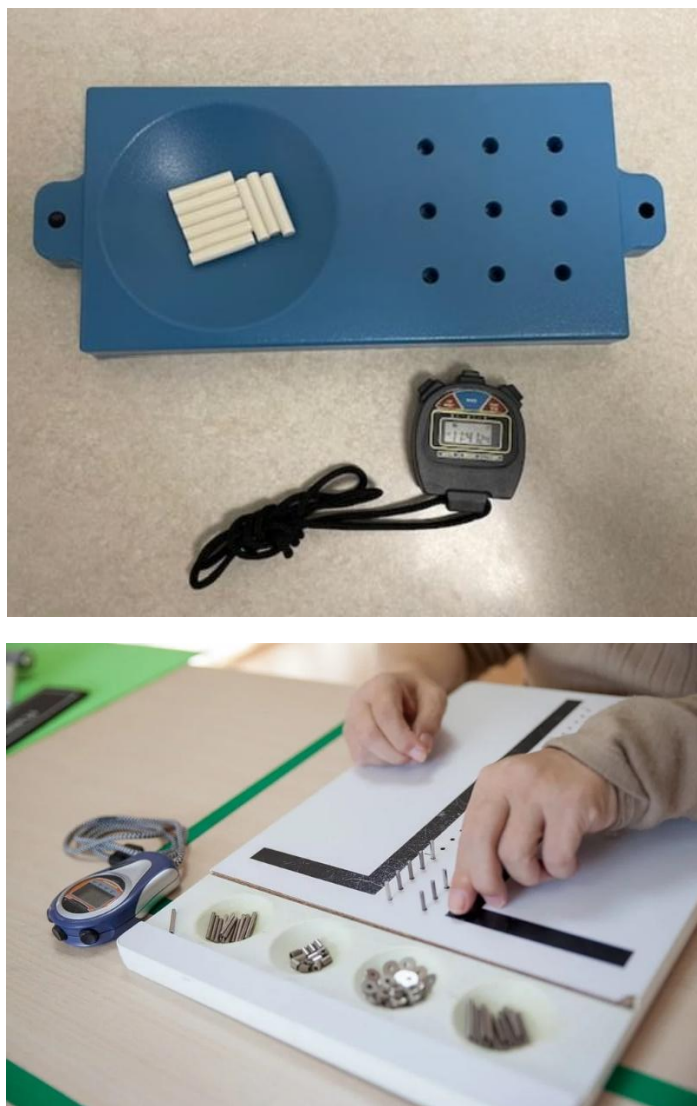


Figure 10: The nine-hole peg test [47] (top) and the Purdue Peg Board Test [48] (bottom)

For both pegboards, the measured variable is the time taken for the participant to complete the test. The tests should be completed multiple times both before and after the motion exposure. The repeated tests allow for a more robust result, and can account for any learning which occurs during the first few repetitions.

5.3.2 Balance-Keeping

In addition to fine motor skills, motion and motion sickness can impact technicians' balance and their ability to move safely inside the nacelle. One experimental setup used in previous research to test this effect is shown in Figure 11, where participants walk on a treadmill while experiencing lateral

motion, and the probability of losing balance is analysed by relating acceleration magnitude to the likelihood of balance loss. This method requires an apparatus that allows testing while the participant is in motion. It can highlight differences in motion responses over the simulation period, providing insights into the cumulative effects of motion throughout the simulation.

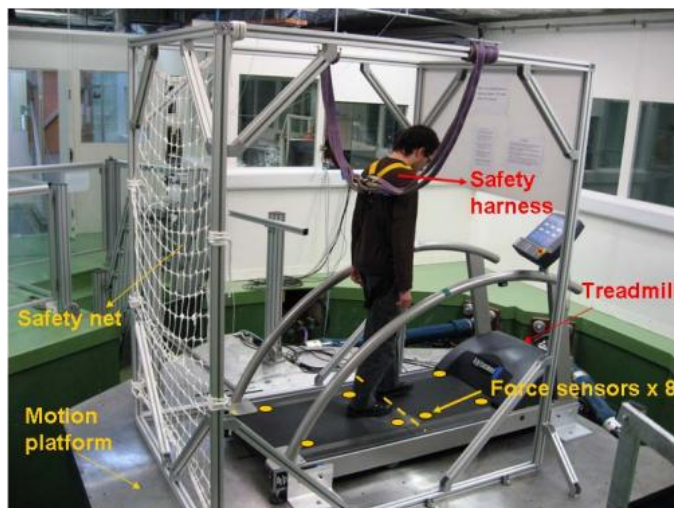


Figure 11 Apparatus for Assessment of Walking Subjects under Lateral Vibration [50]

Alternatively, the 10 Metre Walk Test, which assesses walking speed over a short distance, is used to determine mobility and balance [51], and would be done both before and after undergoing motion. This would allow for a simpler apparatus setup, as the participant would be able to remain stationary while undergoing motion. The test is done by having the participant walk 14 metres, timing the distance from 2-12 metres, and comparing the time both before and after undergoing motion. The test after undergoing motion should be done as soon as possible after egressing the apparatus to limit the impact of 'restabilising' to a lack of motion.

5.3.3 Cognitive Ability

Cognitive ability tests assess the impact of motion sickness on problem solving, response time, and memory. Performed both before and either during or after undergoing motion, these tests are designed to evaluate the change in responses (often response time or accuracy) of each participant.

The Psychomotor Vigilance Test (PVT) is a method for evaluating response time (the time difference between a signal and the participants reaction), often used as a way to measure fatigue. This could be done using a VR headset or screen setup during motion simulation, with a button for participants to press when signalled. The test can be performed before motion begins to baseline values to be collected.

Additionally, participants can respond to questions via a VR headset or secured tablet to evaluate awareness, task accuracy, and memory. This type of test had been used in a multi-task study, with four concurrent tasks, and found correlation between motion sickness and declining performance [52]. A variation of this could be done, with questions relating directly to technician tasks.

5.3.4 Biofeedback measurement

Biofeedback refers to data provided by the involuntary response of the body, such as heart rate, eye motion, and sweat production, to external stimuli. This kind of data, while not directly correlated to cognitive impairment or decline in fine motor skills, allows for a better understanding of the body's response to motion-induced stress and provides an objective measurement for motion effects on

human participants. As with other tests, these would begin before undergoing motion to establish baseline information.

There are several monitoring solutions available which can monitor and record heart rate, respiratory rate, skin temperature, body position, movement rate, and GPS position. Respiratory rate, skin temperature, and heart rate are known to be directly correlated with motion sickness [53], and could be used to objectively evaluate and better understand the physical effects of long exposure to motion.

An additional metric to objectively assess motion sickness and the degree of sensory mismatch felt by human participants is involuntary eye movement. There is a direct correlation between eye motion and visually-induced motion (often seen in virtual reality simulations) [53]. To quantitatively assess eye movement, eye tracking systems have been used in VR headsets to track the response time and focus of eyes to stimuli.

5.3.5 Surveys

As well as empirical testing, motion can also be assessed by testing participants' subjective experience. This allows an understanding of the severity of motion sickness symptoms felt by participants which would otherwise be impossible to track (for instance feelings of dizziness and nausea).

A simple questionnaire has been developed and used in motion sickness applications to assess the degree of illness felt by a participant. The Motion Illness Symptoms Classification (MISC) scale was developed to assess the progression of motion sickness symptoms thorough an 11 point scale from 0 to 10, with 0 being no symptoms at all and 10 being vomiting [54]. The scale is provided in Figure 12.

Class description	MISC
No problems	0
Some discomfort, but no specific symptoms	1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach/throat awareness, burping, blurred vision, salivation, ... but no nausea	2
Vague	3
Little	4
Rather	5
Severe	6
Nausea	7
Little	8
Rather	9
Severe	10
Retching	
Vomiting	

Figure 12: The Motion Illness Symptoms Classification (MISC) or Misery Scale, from [54]

The MISC scores of participants could be compared with the results of empirical testing to assess the correlation between subjective feelings and participants' physical abilities. Additionally, this comparison could be used to identify variation in reporting among participants, as it has been hypothesised that different groups may have a tendency to under or over report symptoms.

5.4 Additional Considerations

When designing an experiment analysing the impact of motion on technician capabilities, there are several aspects that should be considered outside of apparatus design and data collection. These include locational challenges, and experimental constraints.

5.4.1 Locational Challenges

The apparatus selection will influence the testing location. While smaller apparatuses can be relocated to a chosen area, many are designed for a large space or integrated into a larger test facility. The test facility should be accessible for participants to not deter for volunteers.

The location will also affect the pool of volunteers. For example, tests done at universities generally have a larger percentage of younger volunteers compared to the population as a whole. Similarly, testing sites located near pre-existing offshore wind or other offshore asset maintenance bases may enable a larger number of people with relevant experience to be recruited for the experiments.

5.4.2 Time Constraints

The experiment's scale should match the testing duration, ideally as long as a technician is in the moving environment. However, longer tests (up to several hours) may reduce the number of willing participants and increase required incentives. Additionally, longer test durations limit the number of tests that can be performed, which should be considered in the environmental design. Participants also need recovery time after testing, typically one hour. Furthermore, a buffer between participants is necessary to maintain anonymity and protect information.

5.5 Summary: Experiment Design Considerations

This review of methodology to assess motion-induced negative effects on technician performance has suggested several elements to consider when designing such experimentation. There is no one optimum experimental design, rather, test design should consider the following:

1. The necessary sample size to statistically answer the research question

The exact research question that the experiment it attempting to answer should be explicitly defined at the outset. This will allow the necessary sample size of participants and testing requirements to be calculated. For instance, if trying to prove a statistically significant result, a large number of participants may be necessary to define statistical distribution of results. Additionally, different characteristics which are known to affect an individual's susceptibility to motion sickness, such as sex and age, should be considered as part of this sample definition exercise. The likely impact of the proposed testing duration on participant recruitment should also be considered in this stage.

2. Participant safety and confidentiality at the outset and built into the experimental design

Any research with human participants needs to be adequately planned from a safety and ethical point of view to minimise any risk of harm. For this type of research, this planning would need to include:

1. Screening of participants for pre-existing conditions,
2. H&S within the testing apparatus, and
3. Consideration of emergency procedures.

3. The required capability of any motion simulator

There are several motion simulators in the market capable of completely replicating the motion simulated at a FOWT nacelle. However, these machines are expensive to hire and located within research and testing facilities in Europe, necessitating contracting with these organisations, and recruiting participants who either live near that facility or are capable of travel to it. At the same time, there are several simulators located within the UK and available at a cheaper rate, yet do not have the range of motion to completely replicate the most extreme simulated nacelle motion, and would therefore need to “clip” the replicated motion. Selection of a motion simulator should therefore consider the implications of this clipping on the accuracy of the results.

4. The motion-induced effects of interest

As shown, there is a range of tests which could be performed on participants to assess the impact of motion. However, to perform all the tests is likely to be unfeasible due to the time demand. Additionally, a significant number require testing immediately after the cessation of motion, so performing one test may limit the accuracy of others. The experimental design should therefore focus on particular elements of motion. For example, a study may wish to focus predominantly on the effects of motion on dexterity, or on cognitive ability, or on feelings of motion sickness. It would be difficult to cover all three accurately with one test.

Additionally, the combination of tests proposed should also consider the time at which the test is carried out. For instance, biofeedback measurement can be taken while the simulator is in motion, so could easily be incorporated with other testing methods which cannot be performed while the simulation is ongoing.

6 CONCLUSION

This project aimed to investigate the challenge of motion sickness on FOWTs via multiple approaches described in the sections above. The findings from these sections present a complex picture regarding the risk of motion sickness, with key conclusions from each presented below.

6.1 Key conclusions of study

Lack of comprehensive guidance for assessing motion sickness in a FOWT nacelle

At present, there is no clear way to assess the risk of motion sickness caused by the motion of a FOWT nacelle. The literature review indicates two standards which have been used to assess the risk of motion sickness and workability. The NORDFORSK guidance provides limits on acceleration in 4 degrees of freedom, but there is very little indication of the provenance of the guidance, and stakeholders indicated that it may be optimistic. The basis of the ISO 2631-1 standard is known. It's based on experiments which moved human subjects vertically until they were sick. As a result, the standard only considers vertical motion and vomiting. In a FOW context, neither of these standards are suitable, indicating a need for a new standard for assessing motion more similar to the motion of FOWT nacelles.

Modelled motion indicates that motion sickness unlikely to be a problem

The nacelle motion modelled in the OrcaFlex simulations indicates that the level of expected motion for FOWTs in accessible sea states (up to 2.5m Hs) is unlikely to be of a magnitude which causes motion sickness. The horizontal acceleration recorded at the nacelle in a maintenance configuration throughout the simulations is lower than the lowest NORDFORSK limit. Similarly, application of the ISO standard (albeit not under the circumstances it is designed for) indicates a low proportion (less than 7%) of a normal population would experience motion sickness in even the most provocative maintenance conditions considered. A clear difference in motion was observed between the two foundation types considered, with the TLP foundation leading to nacelle acceleration values roughly half those encountered on the semisubmersible FOWT. These results suggest that the foundation choice may have a significant effect on the amount of motion experienced at the nacelle.

Different FOW demonstration sites have varied experiences with motion.

The experiences of technicians at the two demonstrator sites differed. Technicians at the Kincardine site did not experience any significant motion at the nacelle and were not aware of any incidences of motion sickness. In contrast, technicians at the Hywind site did experience significant motion with several reports of motion sickness and mitigating actions reported. This result seems to confirm that the degree of motion and motion sickness felt at the nacelle will be very dependent on the foundation type used on the FOWT.

Methods to empirically explore the effects of FOWT nacelle motion on human operators already available

As highlighted above, motion sickness is likely to be structure specific, and therefore should possibly be considered in the design phase of the FOWTs. However, as the review showed, there are no widely accepted ways to assess the type of motion expected at the nacelles of FOWTs. To develop this type of assessment, empirical, lab-based testing is required. The review of experimental design, motion simulation apparatuses, and testing procedures indicates that the capability to assess the

effects of motion on human operators is already present within the research institutions of the UK and Europe.

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APPENDIX 1 TNO FURTHER ANALYSIS

As noted in the guidance review and also the motion data analysis, the current published guidance on motion sickness is not designed for the type of motion expected at the nacelles of FOWTs. While the current guidance is focussed on heave motion (the most prevalent on vessels), the nacelles of FOWTs are expected to mainly move in a horizontal direction.

Outside of official guidance, there are a number of academic and research institutions which have created models which do account for this motion. One of the most prominent and developed is that created by the research organisation TNO in the Netherlands. The Human factors research team has developed a motion sickness model focussed on issue of motion sickness in driverless cars. This model does take into account horizontal motion and is therefore more applicable for the research aim of this project.

TNO were therefore engaged to perform a standalone piece of work, applying their model to the motion data generated in our OrcaFlex analysis. The work concludes that *“the accelerations computed for the [floating] wind turbines are relatively mild and therefore lead to low predicted probabilities of motion sickness”*. However, the authors also identify a lack of empirical data concerning the extent of FOWT motion, and the resulting motion sickness as a limitation which should be addressed.

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