28th International Ocean and Polar Engineering Conference, 10-15 June 2018, Sapporo, Japan
ISSN:1098-6189. http://www.isope.org/

Whole body vibration on offshore structures: An evaluation of existing guidelines for assessing low frequency motions

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ABSTRACT

An extensive literature research has been conducted to create an insight into the existing norms and standards regulating the assessment of human exposure to motions in offshore environments. A summary of current threshold values and their specific fields of application is included. The presented literature is analysed with respect to their applicability for assessing low frequency oscillatory motions of floating offshore wind turbines to which technicians are exposed during maintenance tasks. The review identifies the need for a consistent assessment method in combination with threshold values for floating structures.

KEY WORDS: Floating offshore wind; motion sickness, human comfort; vibrations; whole-body-vibrations; motion criteria, Operation and Maintenance.

INTRODUCTION

Whole body vibration (WBV) is a comprehensive term for vibrations transmitted to the whole body, not locally to specific extremities (e.g. hand-arm-vibrations), often induced through a seating surface, the backrest or the floor. The frequency, amplitude and duration of the vibrations influence the effects they have on the exposed person. Higher frequencies are associated with more severe health problems, which can persist or occur long after a person was exposed to the vibration, e.g. back pain, (Mansfield, 2005). A distinction is made for WBV in the frequency range below 1 Hz. They are classified as vibrations causing motion sickness and constitute their own class because of the different nature of symptoms they provoke.
The condition of motion sickness is a well-known phenomenon and yet the background of its origins has not been fully unveiled. Familiar under the name of *seasickness* it is mostly associated with high periodic motions on ships and vessels but can equally well occur on aircraft, train, car or roller coaster rides (Griffin, 1990). The symptoms appear in the form of dizziness, nausea and vomiting and are provoked through a conflicting stimulation of the vestibular system and the received visual information. Symptoms cease or disappear when the person is removed from the vibration source, (Mansfield, 2005).
Gresty and Golding (2008, 2009), have investigated the impact of vertigo and spatial disorientation on the performance of different tasks. They found that in the condition of motion sickness, cognitive performance on manual tasks is impaired but that habituation and familiarity to a specific test helps to increase the performance.
It is important to note, that motion sickness is often not identified as such, because it can manifest itself through a feeling of fatigue and apathy, without eliciting nausea. This condition is also known as the sopite syndrome and often results in decreasing work effectiveness. The symptoms impairing performance are not as explicit as vomiting or nausea that come along with vertigo and are therefore often not associated with the motion, (Lackner, 1984; Lackner, 2014).

The decreasing performance caused by motion sickness can become a risk factor, when regarded in a context, where demanding cognitive and spatial tasks need to be performed within a short time window in a moving environment. Maintenance on floating offshore wind turbines will become increasingly significant as the floating wind market is expanding. Following the successful example of Hywind, the first offshore wind park in Scotland, France and Japan are planning ambitious projects for the coming years, (Jimenez 2016). The outlook of exploiting rich wind resources in deeper seas, which are often located far offshore, changes the parameters for the maintenance strategies entailing new challenges for the industry. Offshore, the technical personal is exposed to harsher and more demanding working conditions and the potential reduction of efficiency caused by sickness has great impact on time schedule and maintenance costs. An assessment of non-workable conditions caused by floater motions was performed in Scheu (2018) and suggests that the completion of a maintenance task not only depends on the accessibility of the floater but also on the working conditions that the technicians are exposed to during the repair time. Respecting non-workable conditions for maintenance tasks optimizes the workforce deployment in maintenance strategies.

BACKGROUND

Floating Offshore Wind Turbines On coasts lines, where the seabed reaches depths over 50 m, the installation of offshore wind parks becomes difficult, as the economic feasibility of fixed-bottom structures is reached at this depth, (Henderson, 2009). Countries with a comparable topography reach out to the alternative of floating offshore wind turbines

(FOWTs), which can be installed further outside on the sea above great depths. FOWTs offer the possibility to access the wind resources of more productive regions with stronger and stable winds. Traditional methods for the design and operation process from the offshore wind industry need to be adapted to the additional environmental loads of the regions with stronger winds where the FOWTs are installed.

Floating offshore wind turbines have a different susceptibility to motion than fixed bottom structures. Their natural frequency is lower and closer to the exciting wave frequency. To reduce high motion response a floating wind turbine can be stabilized by different methods: (i) Buoyancy-stabilized, where the broad base of the platform generates a larger shift of the centre of buoyancy, when equilibrium is disturbed. The consequent reaction force renders the structure stable. (ii) Ballast-stabilized, where a heavy weight at the lower end of a cylindrical buoy assures the upright position and creates the stabilization by lowering the centre of gravity closer to the centre of buoyancy. (iii) Mooring-stabilized, where the anchor lines are pulling the buoyancy bodies of the floater underneath the water surface, such that the buoyancy force creates a high tension on the mooring lines, which results in a strong stabilization effect of the whole structure comparable to a fixed bottom system, (Robertson, 2011).

Operation & Maintenance on Floating Offshore Structures The performance of an offshore wind park is influenced by the operability of the wind turbines. The asset operability is the ability to keep the wind turbine in a functioning condition to ensure a reliable performance in a pre-defined manner over its entire usable life. In case of the failure of a crucial component the asset's performance will potentially decrease to zero and the wind turbine will enter a state denoted as "downtime". The downtime of the asset can be divided into two phases: the active and passive maintenance time which are denoted *mean time waiting* (MTW) and *mean time to repair* (MTTR). The MTTR is the average reparation time for the component. The MTW represents the reaction time, which starts with the downtime and ends with the beginning of the reparation work. It consists in one part of the logistical planning of the maintenance work (e.g. personnel, equipment, transfer vessel, spare parts) and in the other of the waiting time for a weather window suitable for the transfer and the pending maintenance task. It is only after the completed access on the wind turbine that the active maintenance time starts. Its duration depends on the complexity of the problem at hand and the capability of the technicians to re-establish the operability of the wind turbine. The nature of the maintenance tasks varies from failure finding through different detection methods to replacements of large and small components of the turbine. The performance requirement for the service personnel varies therefore from technologically advanced cognitive work to heavy manual work. Symptoms like dizziness and nausea can affect the work performance and the execution of the task. In the joint Nordic research project co-ordinated by Nordforsk (Nordic Co-operative Organization for Applied Research) criteria were developed to verify the sea keeping performance of vessels. The collected criteria were summarized in Nordforsk (1987) and are formulated in relation to the activity of the person exposed to the vibration. Motion sickness interferes easier with cognitive work than with physical task and therefore leads to smaller threshold values for the satisfactory magnitudes of motion. The adaption to motion and the resistance against seasickness varies for every individual, which complicates the prediction. High costs for the provision of service vessels and maintenance personal, as well as short reaction times due to small weather windows, however, demand a smooth conduct of repair (and operational) tasks on the wind turbine.

The Quantification of Motion Sickness It is difficult to quantify and to compare the phenomenon of motion sickness, because people react to it with different susceptibilities. In the past, several attempts have been made to predict the occurrences of the phenomenon. A quantification scale was developed by Graybiel (1968) and accounts for a wide range of symptoms which occur at different stages of motion sickness. Lawther and Griffin (1986) also quantified the "vomiting incidence" by using an illness rating, and O'Hanlon and McCauley (1974) displayed their results of the motion sickness incidence (MSI) in a three-dimensional graph. The graph presents the MSI in direct relation to the root mean square (RMS) acceleration and the signal's frequency and was adapted by Benson in 2002. O'Hanlon and McCauley (1974) found the highest MSI at a frequency of 0.167 Hz. The difference, however, towards the neighbouring frequencies that were tested is not significant. At 0.167 Hz two of the tested 20 people vomited, at the adjacent tested frequencies of 0.083 Hz and 0.333 Hz only one person out of 20 experienced emesis. The conclusion coincides with the results from Alexander et al. (1947), who found in an experiment with various frequencies and identical acceleration that the MSI increased when the frequency decreased. The highest MSI was detected for the frequency of 0.22 Hz, which was also the lowest tested frequency. A conclusion to how the MSI would have behaved at lower frequencies cannot be made. It could possibly reach its peak around 0.167 Hz (O'Hanlon, 1974). Further experimental studies are required to confirm this theory (Mansfield, 2005).

METHODOLOGY

The aim is to identify a suitable evaluation methodology and motion criteria that can be applied for the motion assessment of floating offshore wind turbines in maintenance conditions. Results from a motion analysis based on this assessment should be reliable to use for the development of a maintenance strategy, which respects human comfort. Such a strategy would not only consider the feasibility of the access but also the risk of motion sickness on the platform as limiting criterion for maintenance. For this purpose, existing standards, guidelines and expert literature are reviewed concerning their applicability to assessing the low frequency motions of floating offshore wind turbines. Motion exposure threshold values are included, when given in the literature. The presented literature is assessed according to their applicability in the case of low frequency oscillatory motions of floating offshore wind turbines.

ISO 2631-1:1997 The international standard on human exposure to whole-body vibrations introduces a method for the calculation of frequency weighted accelerations. The resulting RMS values can be used to estimate how intensive vibrations affect the human body and to compare different vibration measurements.

To find the weighted acceleration, recommended frequency weighting curves are applied on the measured acceleration-time signal. Alternatively, a digital frequency analysis can be done by using transfer functions to filter the "raw" acceleration data. The frequency weighting accounts for the unequal perception of vibrations by humans over the frequency range. The weighting curves emphasize the amplitudes of motions with a high perception level and underrate the oscillations with a low perception level. The standard suggests that the resulting weighted signal reflects the human response to the vibration.

Griffin (1990) suggests the occurrence of motion sickness for vibrations below 1 Hz with highest occurrences for frequencies of 0.2 Hz. The standard limits the frequency range for motion sickness susceptibility even further from 0.1 Hz to 0.5 Hz. The weighting factors for the low frequency assessment are however given in a broader range between 0.02 Hz and 4 Hz and have the highest factor for frequencies between 0.125 Hz and 0.25 Hz. This way the standard respects the findings of former studies about motion sickness (Alexander, 1947; O'Hanlon, 1974, McCauley, 1976; Lackner, 1984).

For the assessment of motion sickness ISO 2631 (1997) suggests the calculation of a motion sickness dose value, which respects the exposure time to the vibration and only applies to vertical oscillations. The

complex motion combining lateral, vertical and rotatory motions of floating structures is only insufficiently reflected by a vertical motion dose value.
No limits are defined regulating the acceptable values of vibration magnitude for human comfort. The standard respects that those limits change for different applications and are influenced by many factors. Therefore, the ISO 2631-1 (1997) only gives indicative values which describe the reaction to different vibration magnitudes in public transport (Table 1).

Table 1. Reactions to different vibration magnitudes, (ISO 2631-1:1997).

Vibration Magnitude [m/s²]	Perception
< 0.315	not uncomfortable
0.315 - 0.63	a little uncomfortable
0.5 - 1	fairly uncomfortable
0.8 - 1.6	uncomfortable
1.25 - 2.5	very uncomfortable
> 2.0	extremely uncomfortable

VDI 2057-1:2005 The German guideline treats human exposure to mechanical WBV based on the methods of the ISO 2631-1:1997 and respects the European Directive 2002/44/EC (2002). It regulates the assessment and documentation methods of the vibration exposure for the employer. It introduces the daily vibration exposure A(8) which reflects the average vibration exposure of an employer over an eight-hour day with respect to the vibration magnitude and the length of the individual exposure times. The guideline presents exposure limits (Table 2) to which the calculated A(8) value is compared. The action value defines the human perception threshold of vibration and the limit value is the magnitude above which the employer needs take preventive measures if it is exceeded. The described procedure is applicable to every translational or rotatory oscillation in the full frequency range. The evaluation, however, through the given threshold values is only applicable to vibration above 0.5 Hz and for the assessment of rotational motions it is referred to ISO 2631-1 (1997).

Table 2. Exposure Limits for the daily 8-hour vibration dose A(8), (VDI 2057-1, 2005).

Vibration Dose	Limit Value
Action value A(8)	0.50 m/s² (for x, y, z)
Limit value $A_{x,y}(8)$	1.15 m/s² (for x and y)
Limit value $A_z(8)$	0.80 m/s² (for z)

ISO 6897:1984 The standard treats the evaluation of the motion response of fixed structures in respect to the comfort of their occupants. It addresses buildings and offshore structures and regards low frequency motions between 0.063 Hz and 1 Hz. Its precise correlation to low frequency motions makes it a valuable reference for the assessment of motion sickness on fixed offshore structures. Floating structures, however, are explicitly excluded from its field of application. The guideline gives limit curves (Figure 1) in the frequency range for suggested satisfactory magnitudes of horizontal motion, which were built on data acquired for fixed bottom structures. As floating structures have a different motion behaviour, which also includes vertical motions, this is assumed to be the reason why the guideline is not applicable for the evaluation of the motions of floating structures.

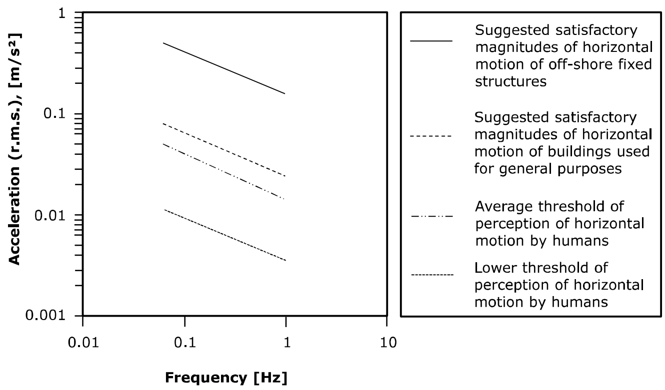

Figure 1. Suggested satisfactory magnitudes of horizontal r.m.s. acceleration in respect to the vibration frequency, (ISO 6897:1984).

ABS Guide for Passenger Comfort on Ships The aim of the ABS Guide for passenger comfort on ships (ABS, 2014) is the combination of all the comfort criteria suitable for passenger ships in one guideline. It is intended for vessels carrying more than twelve passengers for purposes of commuting, travelling, vacationing, and recreating. This guide covers the topics of WBV, noise, indoor climate, and lighting on passenger ships, gives measurement methodologies and limit values for the collection and the evaluation of the required data. For the classification of WBV the guideline introduces the COMF and the COMF+ notation. The COMF notation is only applicable for WBV for frequencies above 1 Hz, which must meet comfort-based vibration level criteria. Furthermore, the COMF+ notation must comply with the motion sickness criteria and covers the low frequency range (0.1 Hz - 0.5 Hz).

DNVGL-OS-A301 The offshore standard DNVGL-A301 (2016) gives limits for noise, vibration, illumination and indoor climate that are to be set on board offshore facilities. The aim is to create an offshore unit with a controlled working environment for general worldwide application. It is primarily written for mobile and floating offshore units, but can also be applied to fixed offshore installations or other units used in the oil and gas industry (ships are excluded). It presents velocity limits related to human comfort and working environment on board offshore facilities, which apply to vibrations in both vertical and horizontal direction and to a frequency range of 1-80 Hz.
The DNVGL-A301 (2016) sets a threshold at 0.0315 m/s² for low frequency motions in a range between 0.5 and 1 Hz, e.g. for slender pedestal constructions. The frequency range of the given limit values lies outside the range of applicability for kinetosis which ranges between 0.1 and 0.5 Hz (Griffin, 1990), and further information on low frequency motions are not given by the standard.

Nordforsk - Assessment of Ship Performance in a Seaway The "Assessment of ship performance in a seaway" was published by the Nordic research collaboration Nordforsk (1987) and aims at improving the knowledge of the seakeeping capability of a vessel. Human comfort on the ship from passengers and crew is one of the investigated aspects. Nordforsk addresses the decrease in performance that arises from critical factors such as deck wetness or motion sickness and therefore provides acceptable values of vibration magnitude required for different audiences or activities on ships (see Table 3). The requirements range from comfort for cruise liner passengers to simple light work where the only concentration must be dedicated to keeping balance. The motion criteria are given for all degrees of freedom (horizontal, vertical, and rotational) and no frequency range for the applicability of the limit values is given.

Table 3. R.M.S. acceleration and roll criteria for human comfort on

vessels for different types of activities, (Nordforsk, 1987).

Root Mean Square Criterion			Description
Vertical accel. [m/s²]	Lateral accel. [m/s²]	Roll [deg]	
1.962	0.981	6.0	Light manual work
1.472	0.687	4.0	Heavy manual work
0.981	0.491	3.0	Intellectual work
0.491	0.392	2.5	Transit passengers
0.196	0.294	2.0	Cruise liner, older people

Nordforsk (1987) has been used as reference in many studies with a wide range of application. Among others, Ghaemi (2017) refers to the motion criteria given in Nordforsk for his general definition of total ship operability. Berg (2015) recommends the application of the Nordforsk criteria for evaluating the performance of vessels during transit. He underlines the importance of relating operating criteria to vessel motion and environmental conditions. Mathisen (2012) uses the Nordforsk criteria for the investigation of the workability on offshore floating fish farms and concludes that the existing standards regulating fish farm motions need to be adapted and oriented on the offshore industry. For structures further out to sea the design criteria need to be changed in order to account for the aspect of human comfort. Buchner (2005) investigated operations of LNG carriers and the behaviour in waves of the assisting tugboats. In the context of quantifying the related weather limits Buchner (2005) refers to Nordforsk's motion criteria. Smith and Thomas (1989) compare different motion criteria for ships and refer among other sources to Nordforsk's motion limiting criteria. Dolinskaya (2009) studies the routing optimization of vessels and refers to Nordforsk for the operational constraints, which are taken into account.

OTO 2001/068 The technical information on noise and vibration exposure to humans on offshore installations are provided in the Offshore Technology Report OTO-2001/068 (2001). The given maximum noise and vibration levels for all installation areas serve as guiding limits in the design process of offshore installations, in order to enable a design process potential noise and vibration problems. In the guideline the RMS acceleration limit curves for horizontal and vertical vibrations in respect to the vibration frequency are given. The frequency range of applicability of the vibration lies between 1 Hz – 80 Hz and is not intended to be extrapolated beyond these limits. This way, OTO 2001/068 does not cover the area in which the condition of motion sickness occurs.

ISO 20283-5:2016 The guideline to mechanical vibration on ships regards the habitability on passenger and merchant ships for passengers and crew. It gives assessment methods for the measurement, evaluation and reporting of vibration. For different areas on the ship acceleration limit values are given in the frequency range of 1 Hz – 80 Hz and serve as guideline value for the evaluation of the motion. It further gives specifications about instruments and measurement procedures. For low frequency motions and the condition of motion sickness, it refers to ISO 2631-1.

NR 636: Comfort and Health on-board Offshore Units This regulation focusses on the habitability of offshore units and provides information about the assessment of exposure values from vibration and noise. The values are evaluated in respect to two different requirements. The first is the comfort requirement, which ensures a calm environment for accommodation, service, navigation and control spaces. The second being the heath requirement, which protects the workers from health, risks due to the exposure. Overall frequency-weighted RMS vibration values in the frequency range 1 Hz – 80 Hz are given as guideline values for the requirements and the working areas.

Other fields of application, apart from offshore engineering, have treated the subject of vibration measurement and their evaluation in respect to human health and safety. The following two standards contain examples from the building and railway industry.

DIN 4150-2:1999-06 The German standard focusses on the effects of vibrations in buildings on persons and contains information for the evaluation of periodic and non-periodic oscillations. Furthermore, it gives reference values, which if exceeded, signify a nuisance for the people under vibration exposure. The considered vibration frequency range is limited to the scope of 1 Hz – 80 Hz. This standard refers to the different parts of the VDI 2057 and applies the therein-described evaluation methodology to the specific field of building vibrations. Low frequency motions below 1 Hz are not treated in this standard.

DIN EN 12299:1999 The standard addresses the ride comfort for passengers in railway applications and describes a method, which calculates a continuous comfort. For this, the measured acceleration time signal is divided into time segments of a fixed duration and from the acceleration values of each segment one weighted RMS value is calculated. This allows an evaluation of the measured track by assigning an RMS value to each segment, resulting in the representation of the RMS variation along the route. Critical track sections can thus be identified. One overall RMS value for the complete time signal would erase all information about the time dimension of the measurement.
A parallel can be drawn to the motion assessment of the nacelle motion during a maintenance task. One workday offshore counts 12 hours, which it can be assumed that approximately 10 hours are spend on the asset and 2 hours are used for boat transfer. During the measured or simulated time peak values of high response amplitudes can occur. They can be initiative for motion sickness but are not reflected by an overall RMS value of the whole time signal. If the assessment is oriented on the evaluation methodology of the DIN EN 12299 (2009) the variation of the RMS value over the duration of vibration exposure can be displayed. This helps to identify how frequently the RMS value exceeds a certain set motion criterion.

CONCLUDING REMARKS

The current guidelines and standards for the assessment of vibrational motions concerning human comfort has been made and the associated motion criteria from different sources has been presented. The literature was investigated regarding its applicability for the maintenance condition on floating offshore wind turbines. A summary of the existing guidelines and their field of application is presented in Table 4. It showed that only a few of the sources are applicable to the low frequency range below 0.5 Hz, where motion sickness occurs or that the given motion criteria is intended for the assessment of ship motions or fixed structures and can thus not easily be applied to the case of FOWTs. In further offshore regions, the environmental impact on the structures rises because wind and wave loads increase, such that

Table 4. Summary of the existing guidelines and their applicability

Standard	Frequency Range [Hz]				Field of Application						Degrees of Freedom for Motion Sickness Assessment		
	<0.5	0.5-1	1-80	>80	No Indica-tion	Fixed Offsh. Struct.	Floa-ting Offsh. Struct.	Ship Motion	Rail-way	Buil-dings	Vert. z	Horiz. x	Rotat. rx, ry, rz
ISO 2631-1:1997	X	X	X	X	X						X		
VDI 2057-1:2005			X		X						not applicable		
ISO 6897:1984	X	X				X						X	
ABS Guide	X	X	X					X			X		
DNVGL-OS-A301		X	X		X	X					not applicable		
Nordforsk (1987)	X							X			X	X	X
OTO 2001/068			X			X	X				not applicable		
ISO 20283-5:2016			X					X			not applicable		
NR 636			X			X	X				not applicable		
DIN 4150-2:1999-06			X							X	not applicable		
DIN EN 12299:1999			X						X		not applicable		

working conditions on FOWTs are more vulnerable to the risk of a decreased working performance on the asset.
Standardization norms for the assessment of human comfort have been developed for fields of application that people are confronted with in everyday life, as for train ride comfort and high building motions. The risk of motion sickness on platforms, however, has not yet been subject to wide discussions. As this review has shown, no standard or guideline can offer a well described method like in DIN EN 12299 for railway applications and in DIN 4150 for building motions. The ISO2631-1 offers methods for the calculations of weighted RMS acceleration values, which can be compared to motion criteria, but for the motion sickness only vertical motions are respected. Criteria are needed in function to the activities performed on the platform, comparable to these given by Nordforsk (1987), specified for maintenance tasks and the field of application must clearly include floating wind turbine substructures.

The loss of manpower through motion sickness has great impact on time schedule and maintenance costs. It is therefore essential to respect non-workable conditions in maintenance strategies and to include the corresponding motion assessment at an early stage in the design process of the floating structures

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 640741 (LIFES50+). A main part of this work was supported by the Chair of Structural Analysis and Dynamics of the RWTH Aachen University and the Offshore Energy Engineering Centre at Cranfield University, as well as Ramboll Energy.

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