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ANALYSIS OF SHIP MOTION ONBOARD A VESSEL X DURING NAVIGATION AND MANOEUVRES

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Abstract

This research will give compliance with the human factor standards in terms of motion on board Vessel X to assess existing human factors standards and their implementation on Vessel X designs. The findings include all technical aspects of the study, such as motion, measurements, analysis, and evaluations. The research methodology developed in this study applies to all classes of ships through the available international standards. The study took full-scale motion on board Vessel X in various ship compartments in stationary conditions and manoeuvres. The measured ship motion compares with current limits for working and living spaces using the international standards for motion such as NATO, NORDFOSK and CCS. Results show that this ship's level of ship motion exceeds the standards set at the international level with the root mean square of rolling up to 2.4°, pitching 4.9°, vertical acceleration 1 G-Force (g) and 0.1 G-Force (g). It shows the risk of having an impact like motion sickness on the ship crew. In addition, several existing human factor criteria might be inferred as insufficient and less relevant to the on board experience. Therefore, they are inefficient in inducing comfort on the vessel under investigation.

Keywords: CCS, Human factor, NATO, NORDFOSK, Ship design, Ship motion.

1. Introduction

Seafarer is a challenging career since the workplace is movable and away for extended durations of time with little chance to meet others. Additionally, seafarers' situation is difficult because they have to balance their relationships with family at home with their employment and living conditions at sea [1]. The Maritime Labour Convention (MLC) has altered the circumstances allowing seafarers protection and rights at work [2]. However, MLC does not protect seafarers working on warships and naval auxiliary units [3].

Vessel X has a highly specialised structure and needs a wide range of functional characteristics. She must have the following attributes: speed, endurance, weapons payload, ability to operate and survive in dangerous areas, and dependability in combat situations. However, ship designs frequently sacrifice some components to achieve this need, and the necessity for personnel needs to be addressed. The crews work overtime and sometimes endure monotonous living and working conditions. Consequently, the circumstance sometimes becomes uncomfortable and hazardous [1]. As a result, fatigue is frequently cited in investigation reports on accident investigations as a significant cause [2].

2. The effect of motion on sleep disturbance

Ship motion is caused by fluid interaction with moving marine vehicles such as ships [4]. Fatigue is caused by lack or poor quality of sleep, insufficient rest time, noise, vibration, vessel movement, and excessive workload [3]. Movement and noise significantly affect sleep quality [5]. In addition, the motion of ships at sea can disturb the balance of the crew, increase energy consumption to balance the body during movement and increase fatigue, drowsiness, and dizziness. Motion can cause operator performance to deteriorate, thus, safety [6]. The motion also causes discomfort in the stomach and causes vomiting [7]. Table 1 explains that motion contributed most to seafarers' fatigue.

Table 1. Contributing factors for fatigue among seafarers.

Attributes	Methodology	Findings	Contributing Factors
Seafarer Mental Health Study [8]	Survey of 1856 seafarers	Over 40% of seafarers reported disturbed sleep due to noise and motion.	Noise **Motion**
Techniques and challenges of human and organisational factors [9]	Systematic Literature Review	Ship motion, noise and vibration affect the crews' performance and will influence strain and fatigue	Noise **Motion** Vibration
Discriminating between fatigue and sleepiness in the naval operational environment [10]	Survey on 767 crew members of a US Navy ship	91.6% of seafarers had their sleep disturbed by noise and ship motion.	Noise **Motion**
Work performance for seafarers [11]	Survey on a random sample of 30 seafarers in Tanzania	The most influential factors on the work performance of seafarers regarding ship specifics are the condition of accommodation spaces, ship vibration, noise, and ship motion	**Noise** **Motion** Accommodation Vibration
Seafarers Work and Rest Hour [12]	Semi-structured interviews	Factors may result in fatigue, such as having noise, vibration, and motion, as well as medical conditions	Noise **Motion** Vibration Medical conditions
Safety behaviour at sea [13]	Survey on 202 seafarers	Fatigue among seafarers attributed to the harsh environment such as time-zone crossing, noise, low or high temperatures and motion	Noise **Motion** Time-zone crossing Low or high temperatures

Seafarers' fatigue [14]	Review of the literature from 11 databases	Several other unique features of the onboard environment of a ship can contribute to insufficient sleep quality. Notable among these features are noise and motion	Noise **Motion**
Habituation of sleep to a ship's noise [15]	Actigraphy Experiment and A Sleep Questionnaire	Exposure to the noise of a typical diesel engine at voyage speed leads to reduced sleep quality measured both subjectively and objectively	Noise
The ship's motion affects crew performance [16]	Questionnaire and Experiment using omnidirectional piezoelectric accelerometer	Motion has been shown to increase the number of wake periods during the night, effectively preventing the body from achieving the deeper stages of sleep required for restorative sleep	**Motion**

Relevant organisations have advised mitigating and managing fatigue at sea during operations [17]. Measures proposed are sleeping patterns, watch schedule, environmental manipulation, workload management and dietary arrangement. In addition, several measures have been addressed to the vessel's design, including providing comfortable accommodations, minimising noise, and vibration, improving indoor climate and providing better working facilities to reduce workload.

Prescriptive guides and voluntary standards on enhancing vessels' design by improving habitability and comfort for the crew are available and ready to apply for a new build vessel. Controlling the environment by design will increase the comfort level of the personnel, give them the opportunity for better sleep and rest, and thus contribute to increasing their performance. For instance, Det Norske Veritas (DNV) publishes an additional comfort class which is divided into two groups: noise and vibration (COMF-V notation) and indoor climate (COMF-C notation) (DNV 2009) [18].

Pitch and roll have a minor impact, but when combined with a heave component, it is insufficient to cause motion sickness. However, the results can be significant. The impacts of "pitch alone" and "roll only" were minimal [3]. Pitch and roll had a more significant impact when paired with a heave in the "pitch plus heave" and "roll plus heave" scenarios. Head motions in the presence of (even minor) vertical motion might cause motion sickness [19].

3. Scope and limitation

Due to limited access to on board measurement warships, this study was only carried out on Vessel X ship as a measurement model to measure the movement on the ship. Any organisation can later use this model to perform measurements on their ships. The standards for ship movement used NATO 2000 [20] and NORDFOSK 1987 [21] standards. The measurement was conducted on board Vessel X during the navigation and manoeuvring at sea.

4. Methodology

An experiment was carried out on board Vessel X from 18 until 24 July 2021. The data was collected during the ship operated in the waters of the South China Sea. In July, the low-level wind flow resembled June, characterised by a slightly stronger westerly zonal wind component than the previous month, stretching from the equatorial Indian Ocean towards the South China Sea to the western Pacific [22].

The vessel criteria were documented through vessels operating at sea measurements concerning motion (roll, pitch, vertical acceleration, and lateral acceleration). Regarding the measurement conditions, the classification society prescribed carrying out measures in standard operating conditions only, i.e. with the ship sailing on a straight course at about 85% of the Maximum Continuous Rating (MCR) [18]. The data for the international standards collected through text mining and content analysis was conducted and used as the reference for measuring the level of application on board.

Environmental influence, like wind speed, is measured during the voyage by an anemometer, and waves are visually observed by officers on duty at the bridge and documented in the ship's logbook (Ships Log). As regards the crew spaces, the following broad subdivision (in order from the most to the less demanding) is used in the comfort class (CCs) under IMO 1981 [23]:

i. Accommodation spaces.

ii. Navigation spaces.

iii. Service spaces.

iv. Workspaces

The motion was measured using Chrystian Vieyra's Physics Toolbox Accelerometer app installed on a calibrated handheld device located on the flat cabin floor and recorded throughout the voyage).

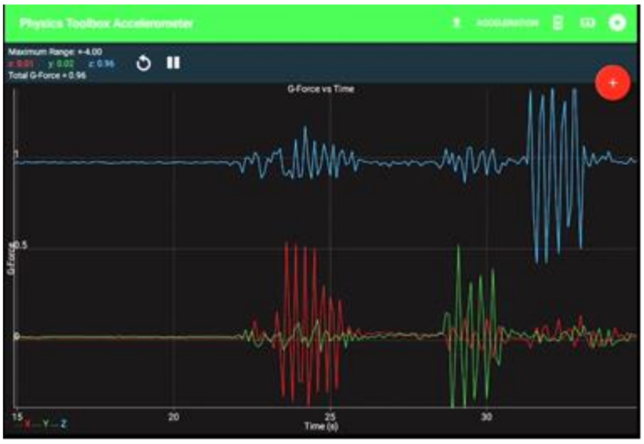

Fig. 1. Chrystian Vieyra's Physics Toolbox Accelerometer Application.

The accelerometer produces an electrical output signal connected to the applied motion alone or with other sensors for data variation. As explained in Fig. 1, it can give the maximum range from the x, y and z axis and the total G-Force. The graph G-Force vs time is plotted in three different colours, which are blue, green and red. Accurate accelerometer calibration is required for quality measurement because it gives physical meaning to the electrical output. The calibration tools included in the software are used to improve the sensor's accuracy. First, the equipment was placed on the known flat surface object on the jetty. The surface onboard is not considered first because it tends to move due to the sea surface motion at the jetty. The error of offset values is obtained using the built-in application calibration feature. Figure 2 shows the calibration results giving the offset data for the x, y and z-axis as it must be close to 0°. Finally, calibration is conducted on the 3 different flat surfaces using the static platform on the shore (flat surface 1/flat surface 2/flat surface 3). The results for calibration are:

x: -0.05102041°/-0.05025293°/-0.05678031°

y: -0.013979591°/-0.012013481°/-0.014023415°

z: 0.008673549°/0.008722361°/0.008432995°

The offset data of the handheld device contains the offset values within +/-0° and is accepted to be used in the motion measurement onboard ships.

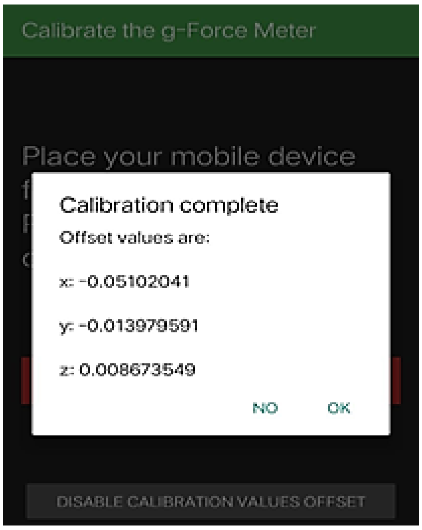

Fig. 2. Calibration.

5. Data Exploration and Analysis

Based on the standards identified through the literature review, field measurements were carried out at Vessel X. Additionally, motion measurements have been carried out at several locations on the ship that focus on accommodation spaces and workspaces that require crews to always be in the area (Table 2).

5.1. Motion measurement test

The analysis of the motion tests involves roll readings, pitch, and vertical and lateral acceleration. It was measured using a Chrystian Vieyra's Physics Toolbox Accelerometer application installed in a calibrated handheld electronic device. It is placed at the location in Table 2 with the standard value for motion.

Table 2. Standards for Motion

Category	NATO (2000) [13]	NORDFOSK (1987) [14]
Roll		
Accommodation	4°	6°
Bridge	4°	6°
Engine Control Room	4°	6°
Pitch		
Accommodation	1.5°	-
Bridge	1.5°	-

Category	NATO (2000) [13]	NORDFOSK (1987) [14]
Engine Control Room	1.5°	-
Vertical Acceleration (z)		
Accommodation	0.20g	0.20g
Bridge	0.20g	0.20g
Engine Control Room	0.20g	0.20g
Lateral Acceleration (y)		
Accommodation	0.10g	0.10g
Bridge	0.10g	0.10g
Engine Control Room	0.10g	0.10g

5.2. Roll and pitch

Referring to Table 3, the measurement of roll and pitch onboard Vessel X are based on the NATO (2000) [13] NORDFOSK (1987) [14] standards. The highest standards are chosen because Vessel X is a warship in nature which should withstand the higher standards compared to merchants that prioritise comfort. The measurement location is decided based on the comfort class (CCs) under IMO 1981 [23], which separates the in order from the most to the less demanding, starting with accommodation, navigation, service and workspaces.

Table 3. Summary of criteria vs data from measurements of Roll and Pitch on the ship

Category	NATO (2000) [13]	NORDFOSK (1987) [14]	Maximum Reading Onboard	Comparison with standard
Ship heading to bearing 014° towards the Southwest, the wind from the North with a speed of 10 Knots				
Roll				
Commanding Officer Cabin	4°	6°	4.4°	-1.6°
Senior Rates Accommodation	4°	6°	3.2°	-2.8°
Junior Rates Accommodation	4°	6°	5°	-1°
Bridge	4°	6°	4.7°	-1.3°
Engine Control Room	4°	6°	3.3°	-2.7°
Pitch				
Commanding Officer Cabin	1.5°	-	1.7°	+0.2°
Senior Rates Accommodation	1.5°	-	2.2°	+0.7°
Junior Rates Accommodation	1.5°	-	4.2°	+2.7°
Bridge	1.5°	-	1.9°	+0.4°
Engine Control Room	1.5°	-	1.8°	+0.3°

5.2.1. Rolling movement

Based on NATO standards [20], the Root Mean Square (RMS) angle for rolling a ship must not exceed 4°. Therefore, the measurement readings in Vessel X provide data above the set standards. However, the RMS reading for the rolling angle of Vessel X is still within the standard set by NORDFOSK [21] and does not exceed 6°, allowing light manual work to be performed. It should not involve heavy, prolonged work such as patrolling and escorting ships.

Table 4. Rolling movement Vessel X.

	Officers Cabin	Senior Rates Cabin	Junior Rates Cabin	Bridge	Engine Control Room
Maximum	-0.6°	2.8°	-2.2°	-0.5°	3.8°
Minimum	-1.3°	-3.0°	-8.1°	-4.2°	-4.2°
Min	-0.4°	1.5°	-0.6°	-0.5°	-0.5°
RMS	0.6°	2.4°	2.0°	1.2°	0.7°

Based on Table 4, the Officer's Cabin recorded the lowest RMS reading of 0.6°, followed by the Engine Control Room at 0.7°. This reading is because these two rooms are in the midship. Meanwhile, Senior Rates Cabins recorded the highest reading, and it was on the same deck as Junior Rates Cabins Accommodation. Even though the Senior Rates Cabins and Junior Rates Cabins are on the same deck as Machinery Control Room, both readings are higher because they were located at the ship's stern and bow. The direction of the ship when this reading is taken is 014° with a current towards the Southwest and the wind from the North with a speed of 10 Knots. The positive sign indicates the roll on the starboard side, while the negative is on the port side. Based on the data, the ship's bow is currently experiencing resistance from wind, waves and currents that cause the bow to be more affected by the roll from other parts astern, as illustrated in Fig. 3.

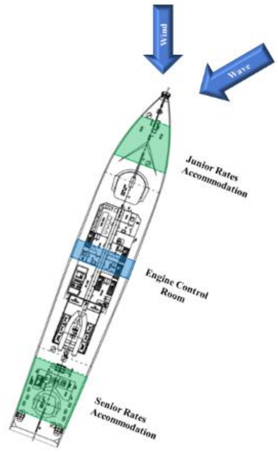

Fig. 3. Wind direction and wave during the measurement.

For Officer Accommodation located on Deck 01 and Bridge on Deck 02 showed 4.4° and 4.7°, respectively. The higher column position increases the roll rate as Deck 01 (4.4°) ascends to (4.7°) for the reading in Deck 01, as illustrated in Fig. 4.

The overall rolling data of Vessel X clearly shows that it tends to tilt to the port side with a maximum angle reading of -12.1 ° (port side) compared to the rotation to the right, which is a maximum of 0.2°. Figure 3 indicates that currents and waves have a more significant effect than the wind, which was only 10 Knots from the direction of the ship's bow. This information can be used as a guide to the Bridge Duty Officer who steers the ship to pay more attention to the effects of these currents and waves because the impact is more significant, as shown in the graph in Fig. 5.

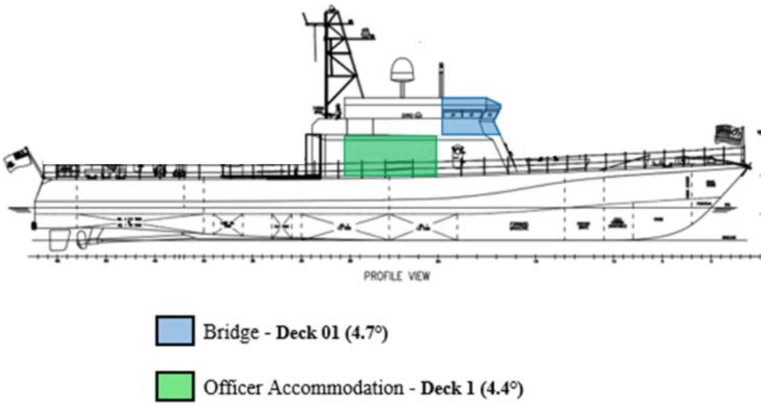

Fig. 4. Position of officer accommodation and bridge.

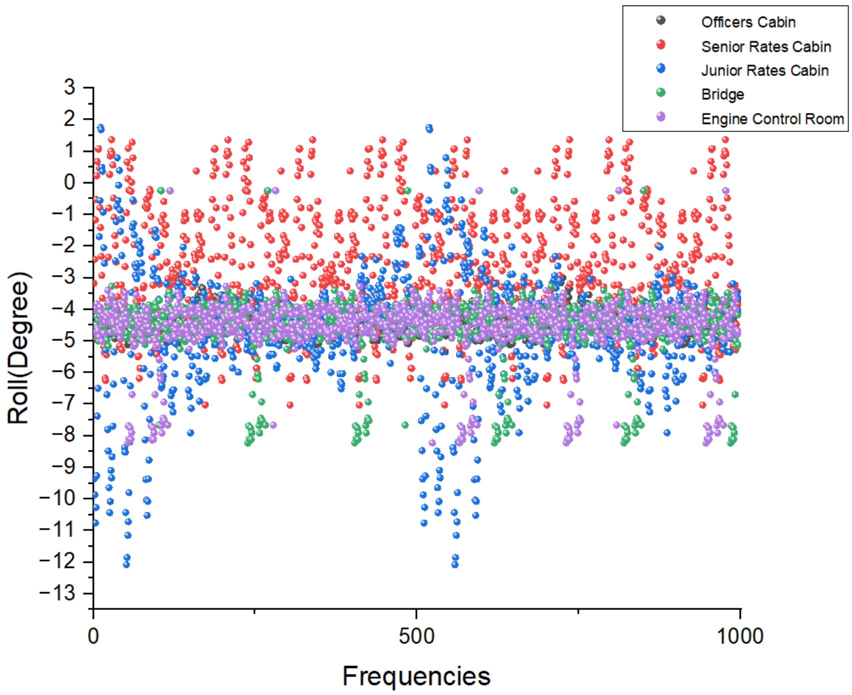

Fig. 5. Rolling Graph Vessel X. The positive indicates the roll on the starboard side, while the negative is on the port side.

5.2.2. Pitching movement

Pitching movement or rotation on the horizontal axis for Vessel X is not specified in the standard in NORDFOSK [21] but in NATO [20], RMS should not exceed 1.5°. Therefore, for Vessel X, the RMS readings were beyond the standards set for all areas in the vessel, as illustrated in Table 5.

The readings in Table 5 show that measurements above the standard are due to currents, waves coming from the left side of the ship's bow and wind blowing from the ship's bow direction, as illustrated in Fig. 3. This effect has caused the swing angle to be significant for the ship with only 43.6m long and must be affected by the weather, as illustrated in Fig. 6.

Table 5. Pitching movement Vessel X.

	Officers Cabin	Senior Rates Cabin	Junior Rates Cabin	Bridge	Engine Control Room
Maximum	3.1°	2.6°	4.1°	4.9°	3.1°
Minimum	0.4°	0.4°	2.6°	-1.0°	0.4°
Min	1.6°	2.1°	4.2°	1.4°	1.9°
RMS	3.1°	2.6°	4.1°	4.9°	3.1°

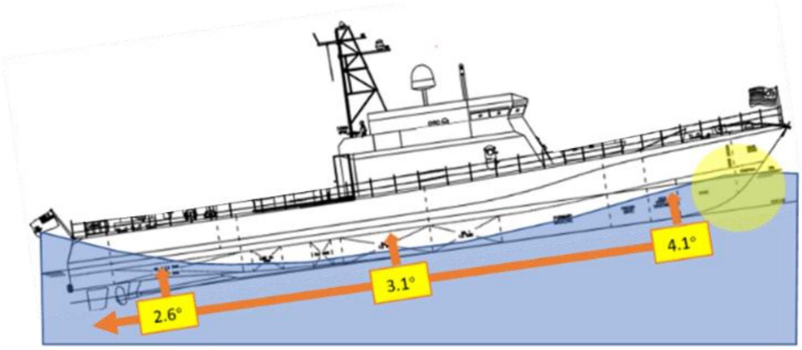

Fig. 6. RMS pitch decreases as it moves further away from the area colliding with wind and waves.

The pitch reading of the Senior Rates Accommodation located at the ship's stern is the lowest. Wind and wave conditions, as described above, improve spaces closer to the bow. The farther the room is from the area that collides with the wind and waves, the lower the pitch reading. The position of the space closest to the bow on Deck 02 is Junior Rates Accommodation (4.1°), followed by Machinery Control Room (3.1°), and lastly, Senior Rates Accommodation (2.6°), as illustrated in Fig. 6. The Junior Rates Accommodation position in the ship's fore compartment prompted this significant movement. This movement is because the ship faces the wave and wind from ahead during the measurement, making the front side cline up compared to the stern part.

The pitch reading for the Officer's Accommodation located on Deck 01 also showed a reading of 3.1°, and the reading increased when ascending to the Bridge located on Deck 01 with a reading of 4.9 ° (Fig. 7). The reading on the Bridge is the highest reading on this ship due to Bridge's position on the highest deck on this ship. This reading explains that the higher the position, the higher the reading angle for the pitch movement of the ship, supporting findings from Spyrou in 2022 [24].

As depicted in Fig. 8, Junior Rates accommodation space experience high and rapid pitching movement (blue dotted Fig. 8) compared to other compartments. Based on this situation, this pitch movement was the most affected, disturbing their comfort, especially in their accommodation.

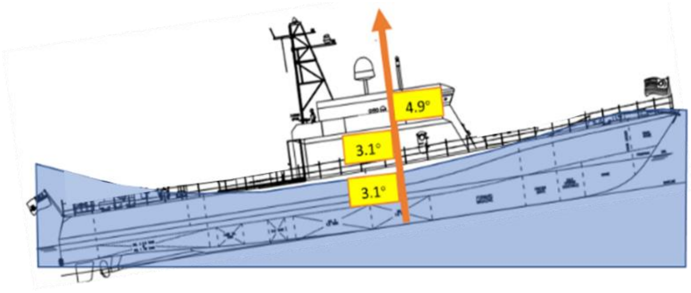

Fig. 7. RMS pitch increase on the increased height of the compartment.

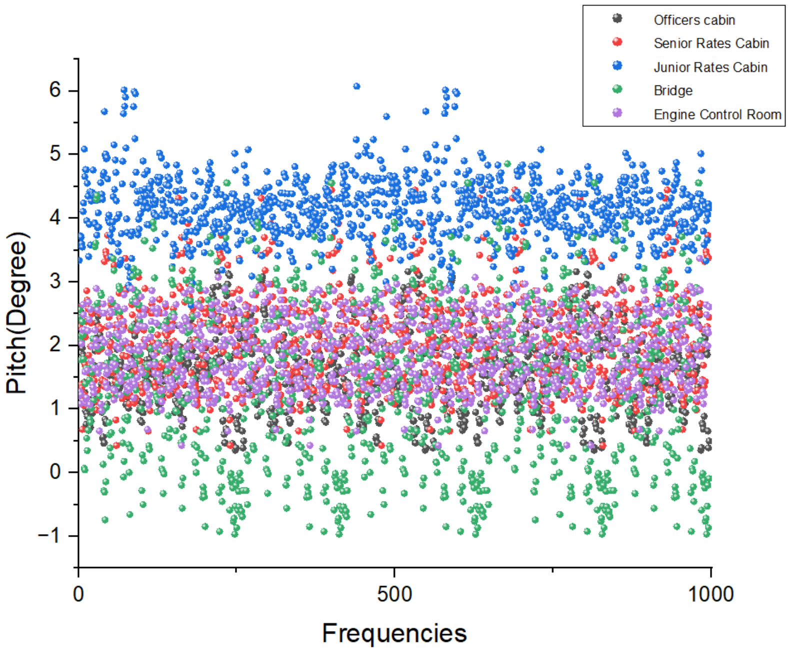

Fig. 8. Pitching graph for Vessel X.

5.3. Roll and pitch

Vertical and lateral acceleration is measured in G-Force (g) units at several locations. In addition, the measurement is on the ship, such as Officer Accommodation, Senior Rates Accommodation, Junior Rates Accommodation, Bridge and Machinery Control Room, as shown in Table 5.

5.3.1. Vertical acceleration (z)

The vertical acceleration compares based on NORDFORSK [21] standards. The highest measurement is 1.0 G-Force (g) RMS, recorded at Bridge. It occurs in state 3 sea conditions and is about 3 m wave height, as depicted in Fig. 9.

Table 6. Summary of criteria vs. data from vertical and lateral acceleration measurements onboard Vessel X.

Category	NATO [20]	NORDFOSK [21]	Maximum reading onboard	Comparison with standard
Ship Heading: 014°				
Vertical Acceleration (z)				
Officers Cabin	0.20g	0.20g	1.00g	+0.80g (400%)
Senior Rates Accommodation	0.20g	0.20g	0.99g	+0.79g (395%)
Junior Rates Accommodation	0.20g	0.20g	1.00g	+0.80g (400%)
Bridge	0.20g	0.20g	0.99g	+0.79g (395%)
Engine Control Room	0.20g	0.20g	0.99g	+0.79g (395%)
Lateral Acceleration (y)				
Officers Cabin	0.10g	0.10g	0.04g	-0.06g (60%)
Senior Rates Accommodation	0.10g	0.10g	0.01g	-0.09g (90%)
Junior Rates Accommodation	0.10g	0.10g	0.02g	-0.08g (80%)
Bridge	0.10g	0.10g	0.10g	0g
Engine Control Room	0.10g	0.10g	0.01g	-0.09g (90%)

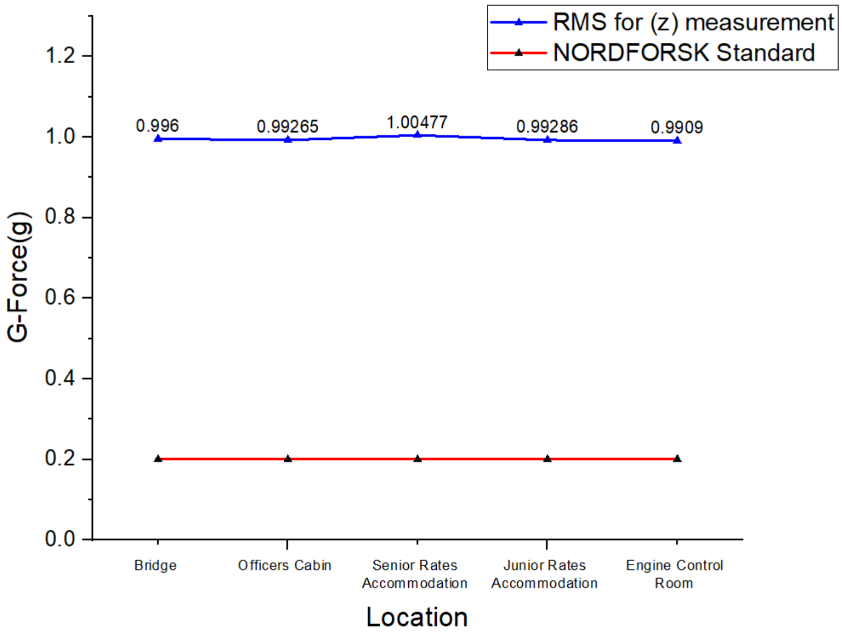

Fig. 9. RMS vertical acceleration (z) for Vessel X.

5.3.2. Lateral acceleration (y)

The lateral acceleration readings at all locations were recorded below the maximum values below 0.1 G-Force (g), compared to the standards by NATO [20] and NORDFOSK [21], as illustrated in Fig. 10.

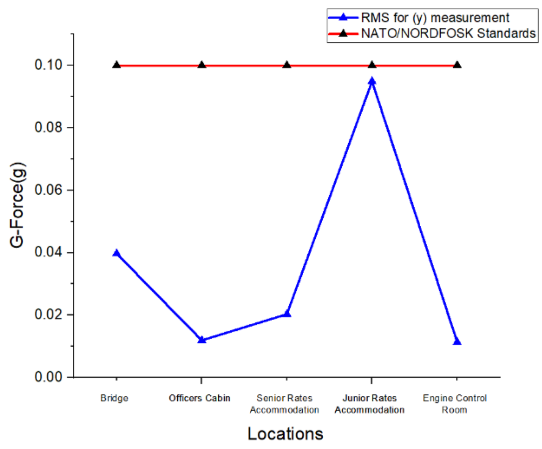

Fig. 10. RMS lateral acceleration (y) for Vessel X.

Figures 9 and 10 show graphs for the data recorded during the survey. The highest RMS accelerations measured were 0.1 G-Force (g) (lateral) and 1.0 G-Force (g) (vertical). NATO [20] standards and NORDFORSK [21] operational limits for "light manual work" have been set for lateral (0.10g) and vertical (0.20g). The measurement results found that the horizontal acceleration was within the standard while the vertical acceleration exceeded the set limit of 0.80g (80%). Based on the pitching (4.9º), which is above the set standard (1.5º). It can be observed that this ship is affected by the movement of the pitch, especially when facing the waves and wind from the bow, thus affecting the vertical acceleration reading.

The standard still allowed "manual heavy work" to be performed on ships with vertical acceleration limits of 0.15 G-Force (g), transverse 0.07 G-Force (g) and roll movement of 6.0 ° [21]. It is highly unsuitable for heavy work on this ship, even if it is new in code 2 sea conditions. Experience onboard shows that it is difficult for citizens to walk safely without hitting walls or other objects. The opinion that "manual heavy work" can occur safely in such circumstances is unacceptable and disrupts the crew's rest time, including bedtime. This standard clearly shows that Vessel X is unsuitable to operate for an extended period at sea because it does not prioritise human factors during its construction. It also stated in the operating doctrine of Fast Attack Craft that the ability to survive at sea for an extended period and seakeeping of this ship is not up to the standard. It was built for the rapid attack at sea and not for patrol or escort operations that take a long time at sea.

In determining the tendency for Vessel X to have motion sickness, the level of pitching, rolling and vertical acceleration are used as the reference based on the model from A.H. Wertheim, 1998 [3]. This study shows that the ship hull's motion for rolling's is still within the standard set by NORDFOSK [21], which does not exceed 6°, which only allows light manual work to be performed. For pith motion, NATO [20] specified that RMS should not exceed 1.5°, but the motion exceeds the standards set in this measurement. In measurement for vertical acceleration, NORDFORSK [21] give the highest vertical acceleration must not exceed 1.0g RMS. However, the data exceeded the set limit in this measurement, which is 80% higher for vertical motion. All crews' motion sickness risk is severe, referring to the ship motion standards. With the root mean square exceeding the standards for almost all criteria which are rolling up to 2.4°, pitching 4.9°, vertical acceleration 1 G-Force (g) and lateral acceleration 0.1 G-Force (g), the likelihood that head movements made in the presence of (even relatively minor) vertical motion facilitate motion sickness reflects the well-known fact that a functioning vestibular system is a prerequisite for motion sickness.

6. Conclusions

In conclusion, as observed on the ship, when the wave height of only 3m on a ship with a length of 43.6m, it has given an effect that does not support the human factor when the ship is operating, especially in adverse weather. There is nothing to do except sit neatly or stand up straight and hold on to something safe to keep balance. The available human factors criteria are unrealistic and cannot be applied by the crew of this ship. Based on this study, some of the existing human factor criteria should not be implemented on Vessel X operating in the waters of the South China Sea. Such criteria must be reviewed and studied to suit the ship's operating role. It is acknowledged that the performance of the citizens on board Vessel X is not solely influenced by habitability or comfort on board but also by several other factors such as duty schedule, alertness, season, and environmental conditions.

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