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Effect of criteria on seakeeping performance assessment

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Abstract

The overall performance of ships depends on the seakeeping performance in specified sea areas where the vessel is designed to operate. The seakeeping performance procedure is based upon the probability of exceeding specified ship motions in a sea environment particular to the vessel's mission. Given the operational area of the vessel, the percentage of time the vessel operates in a particular sea state can be determined from an oceanographic database through application of the response amplitude operators. The predicted motions are compared to the motion limiting criteria to obtain the operability indices. However, the operability indices are strongly affected by the chosen limiting criteria. This is particularly the case for passenger vessels where many conflicting criteria are used to assess the effect of motions and accelerations on comfort and well-being of passengers. This paper investigates the effect of seakeeping criteria on seakeeping performance assessment for passenger vessels. Conventional seakeeping performance measures are evaluated for various levels of vertical accelerations defined by the ISO 2631 standard. It is shown that the estimated seakeeping performance of a passenger vessel greatly depends on the level of limiting value selected as the seakeeping criteria.

Keywords: Seakeeping; Seakeeping criteria; Motion sickness; Habitability

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1. Introduction

Most passenger vessels are designed to operate in an environment which can be hostile due to winds and waves. Regardless of the type or size of these vessels, the well-being of passengers will be degraded by the adverse effects of the environment. Therefore, the technological success of passenger vessels hinges upon a good seakeeping design. It should be the objective of the designer to minimise this degradation and ensure that the safety of passengers on board is achieved.

The seakeeping performance of a passenger ship can be defined in terms of the average fraction of time that the actual motions and accelerations are below specified levels (habitability). An improvement in habitability will obviously improve the well being and safety of both the passengers and crew on board.

The assessment of seakeeping performance of a passenger vessel in a specified sea environment is related to four factors:

- the wave response characteristics of the ship which depends on the size, dimensions, form, and weight distribution characteristics
- the nature of the sea environment
- the ship's speed and heading which determine how the ship will encounter the environment, and
- the quantitative and qualitative requirements for the well being and safety of passengers and crew on board, i.e. the seakeeping criteria

The way these components interact will determine the habitability of the vessel.

It is now common practice to predict the seakeeping responses of a new design in specified sea areas by using 2D or 3D analytical methods and a wide range of seakeeping software are commercially available. The main difficulty in seakeeping performance assessment is, generally, to determine the magnitude of seakeeping responses which will cause degradation of performance.

Operational consequences of seakeeping performance for a passenger vessel are closely related to vertical and lateral accelerations. The effect of vertical accelerations on humans is well understood and has been incorporated into International Standard ISO (1985, 1997). The standard provides severe discomfort boundaries for motion sickness as a function of acceleration level, the frequency of acceleration, and the duration of exposure to the acceleration.

Besides the international standard, other measures could also be employed. These measures include motion sickness incidence (MSI) parameter (O'Hanlon and McCauley, 1974) which reports the percentage number of people who will become motion sick at a given acceleration level, frequency, and duration of exposure, and motion induced interruptions (MIIs) (Graham, 1990) which represent the number of loss-of-balance events which occur during an arbitrary deck operation.

In order to illustrate the effect of chosen seakeeping criteria on seakeeping performance assessment, a 50-m motoryacht is considered. Main particulars and body plan of the vessel are presented in Table 1 and Fig. 1, respectively.

Table 1
Main particulars of the vessel

Length overall (L_{OA})	49.90 m
Length between perpendiculars (L_{BP})	43.10 m
Beam (B)	9.75 m
Draught (T)	2.75 m
Displacement (Δ)	558.1 t
Block coefficient (C_B)	0.485
Midship section coefficient (C_M)	0.696
Prismatic coefficient (C_P)	0.697
Waterplane area coefficient (C_{WP})	0.821
Longitudinal centre of buoyancy (LCB)	5.5%L (aft)
Design speed	17 knots

The presentation of paper begins with an overview of seakeeping performance assessment procedure. This procedure is first used to predict seakeeping responses of the vessel in specified sea states. The habitability in each state is then estimated for a range of acceleration levels described by the international standard as the threshold value for varying levels of discomfort. For each acceleration level, the habitability is evaluated for a range of forward speed and wave headings. The effect of selected acceleration levels on seakeeping performance is described as a function of the habitability index.

2. Seakeeping performance assessment

The assessment of a marine vehicle's seakeeping performance is based on the character of its oscillations in the sea states it is expected to encounter during its operating life. Fig. 2 illustrates an overview of the seakeeping performance assessment procedure. The procedure starts with prediction of the hydrodynamic response characteristics of the vessel for a range of speed and heading values. The magnitude of the motions in seas of varying

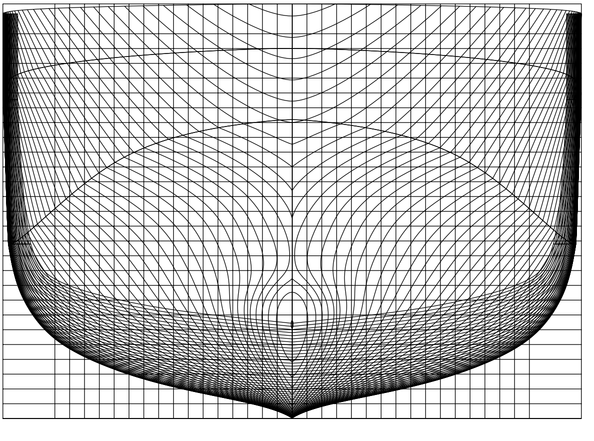

Fig. 1. Body plan of the vessel.

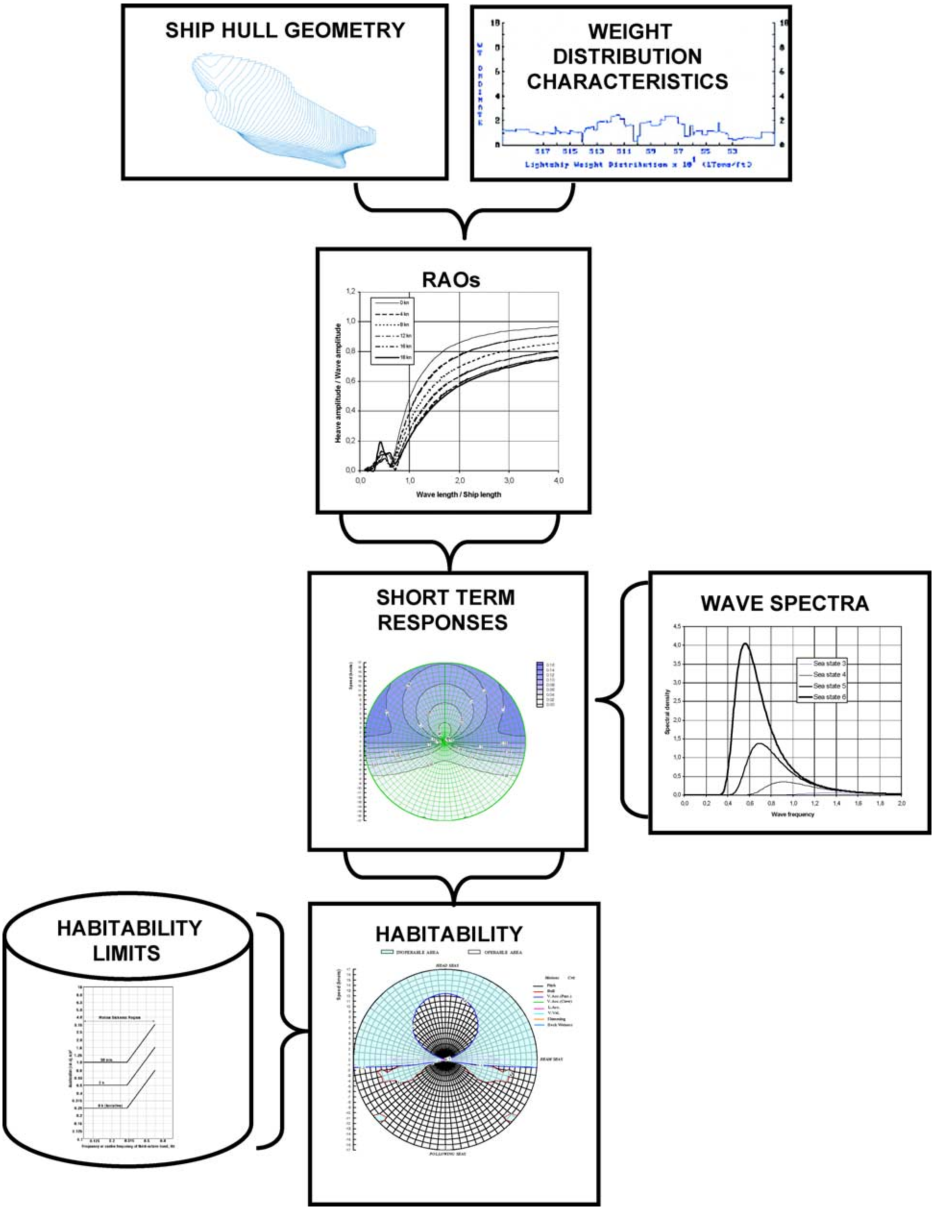

Fig. 2. Overview of the seakeeping performance assessment procedure.

severity can then be predicted, utilising wave spectra representative of the selected operational sea area. Finally, the habitability of the vessel can be estimated, based on the probability of ship motions remaining within acceptable limits.

The steps required to complete such analysis are described in the following sections.

2.1. Ship response characteristics

The first step in the assessment of seakeeping performance is usually to determine the motion response amplitudes and phases in the frequency domain for all six degrees of freedom. Response Amplitude Operators (RAOs) are then computed for each critical mode of motion, i.e. angular motion or translation of any point on the vessel, in terms of displacement, velocity or acceleration. The RAOs define the amplitude of the response due to a unit wave excitation.

Heave, pitch and roll require particular mention because they are three motions with hydrostatic restoring and therefore possess natural response periods and the potential for resonance behaviour. For a passenger vessel vertical and lateral accelerations are of main concern due to the effect of accelerations on the comfort and well being of the passengers.

Fig. 3 shows typical vertical acceleration transfer functions in head seas as a function of wave frequency and forward speed.

2.2. Definition of the seaway

The regular waves are seldom found in nature and hence the RAOs are of little consequence on their own. The natural seaway in which a ship operates can only be described by means of a statistical model. The spectrum or spectral density function is the primary device used for representing the seaway and the oscillatory response of the vessel to the seaway.

The wave characteristics of an area must be known in terms of the distribution of wave energy with respect to frequency and direction, as well as the severity of seas as indicated

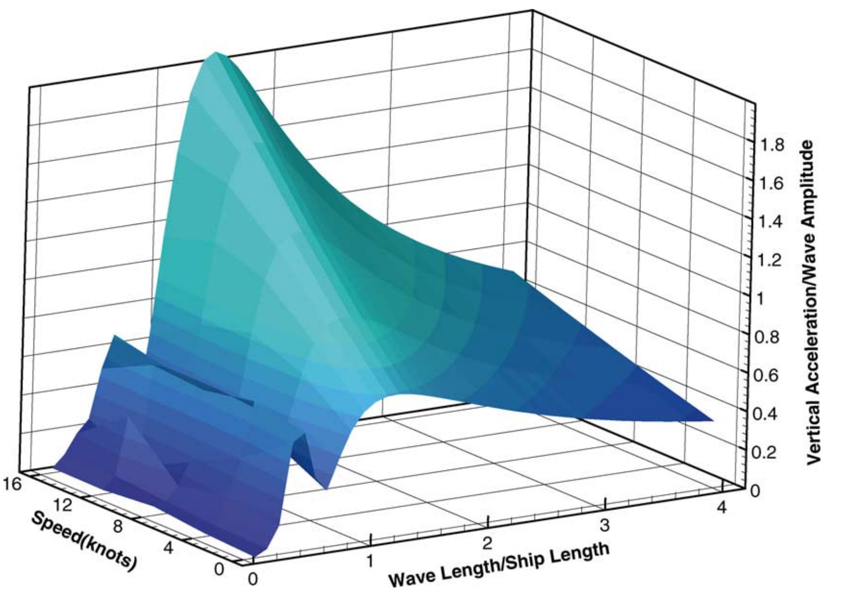

Fig. 3. Vertical acceleration RAOs (in passenger saloon) in head seas.

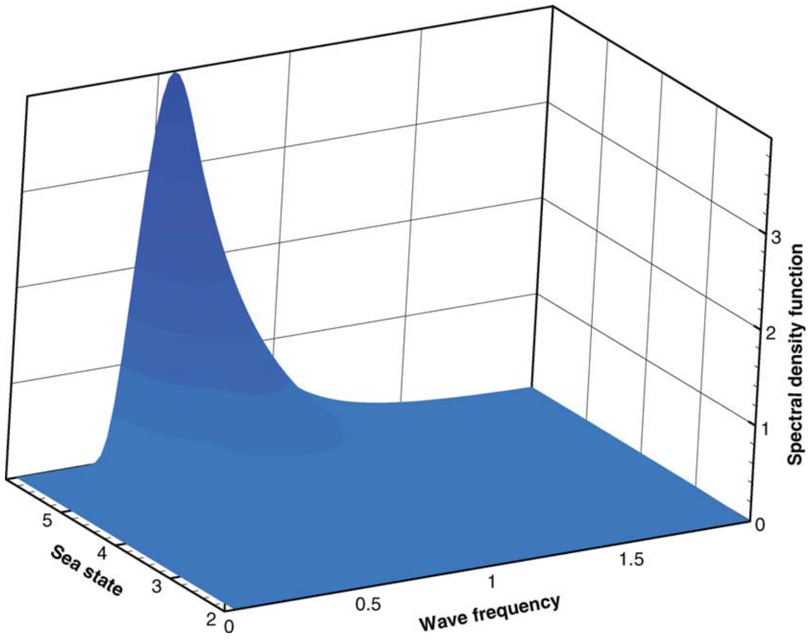

Fig. 4. One parameter representation of spectral density distribution.

by the wave height probability distributions. The wave energy distribution within various wave height bands can be represented through the use of a wave spectral family. In Fig. 4 spectral density functions are presented as a function of wave frequency and sea state, based on the one parameter Pierson–Moskowitz formulation.

2.3. Prediction of responses in a specified seaway

The short-term response trends obtained by superposition of the vessel RAOs with the wave spectral family describe the mean steady-state response amplitudes for seas of varying severity, as well as the standard deviation about the mean due to variations in spectral shape within each wave height group.

A typical result for vertical accelerations in passenger lounge in head seas is presented in Fig. 5. These results are based on calculations for a speed range of 0–17 knots and a sea state range of 2–6.

These calculations must be performed for all headings and for each seakeeping response which may affect the performance of the vessel. Typical examples are shown in Figs. 6 and 7. In these figures the root mean square (RMS) vertical acceleration levels (m/s^2) in passenger saloon are plotted for a range of headings from head seas to following seas, for sea states 5 and 6. The acceleration levels are selected in accordance with levels described by the ISO 2631 standard for different exposure times. Circles in the figures represent forward speed while the radial lines represent the wave heading.

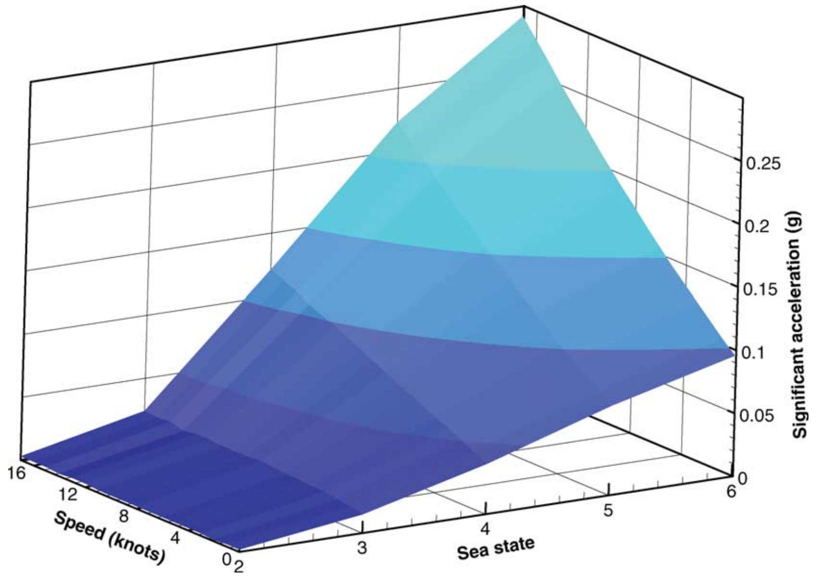

Fig. 5. The variation of vertical accelerations with speed and sea state in head seas.

2.4. Seakeeping criteria

In order to assess the effect of seakeeping performance on the mission capability of the vessel the mission requirements need to be translated into seakeeping performance requirements. However, there is no distinct universal set of criteria for seakeeping performance. The criteria can vary vastly from ship to ship depending on the missions of the ship.

An important key to the acceptability of a passenger vessel is the ride comfort expressed as a low percentage of passengers getting seasick in rough seas. Vertical and lateral accelerations are mainly responsible for seasickness.

Table 2 presents a tentative scale for vertical acceleration, which may be used for estimating the maximum acceptable magnitude for different activities on board and for the comfort of the crew and the passengers.

Typical performance criteria for personnel performance in a warship are listed in Table 3. These criteria are given as significant single amplitude which is the average of the one-third of highest amplitudes and is close to what the trained observer would estimate the motions to be.

The concept of Motion Sickness Indicator (MSI) was developed in a study sponsored by the US Navy in the early 1970s to investigate the effect on humans of ship motions (O'Hanlon and McCauley, 1974). The research attempted to quantify the incidence of actual vomiting (emesis) of a group (over 500) of young men, unacclimatized to motions, subjected to vertical sinusoidal vertical motion of various amplitudes at a series of single frequencies. The range of RMS acceleration and frequency was selected as 0.27–5.5 m/s^2 and 0.083–0.700 Hz, respectively.

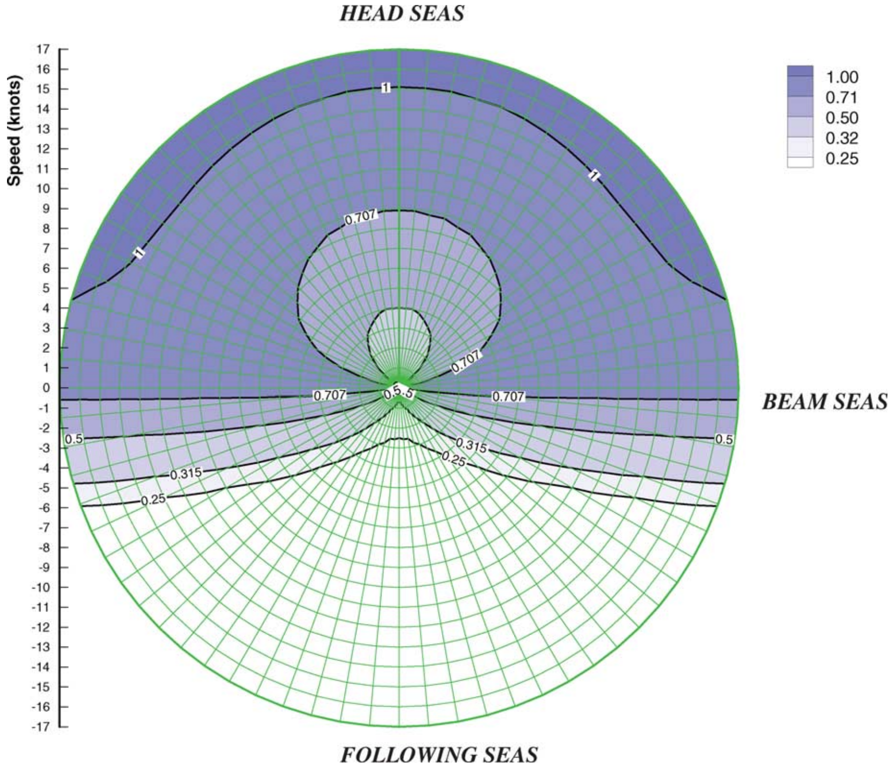

Fig. 6. Speed polar diagram of RMS vertical acceleration in sea state 5.

The experiments showed that the occurrence of emesis was correlated with both acceleration and frequency and, using empirical data, a motion sickness incidence relationship was derived. The MSI value indicates the percent of subjects that experienced emesis in a 2-h test period. According to the test data, people have significantly less tolerance to vertical motion in the 0.2–0.16 Hz (5–6 s) range than at higher or lower frequencies. This is in accordance with experience on ships at sea.

Results of these experiments are often expressed in terms of the acceleration level found to cause 10% of the subjects to become physically ill when subjected to such motions for a specified time interval. It should be noted that, the validity of the MSI is tied to the many constraints imposed by the laboratory environment. The subjects used in the experiment were all healthy young college males, unacclimated to any form of shipboard motion. Furthermore, the effect of roll and pitch motions are ignored.

Motion induced interruptions (MIIs) represent the number of loss-of-balance events which occur during an arbitrary deck operation (Graham, 1990). It was shown that the incidence of MIIs could be related to a concept of lateral force estimator (LFE), which is a combination of the earth-referenced lateral acceleration and the ship-referenced lateral acceleration due to roll motion. This greatly reduces computational efforts since the LFE

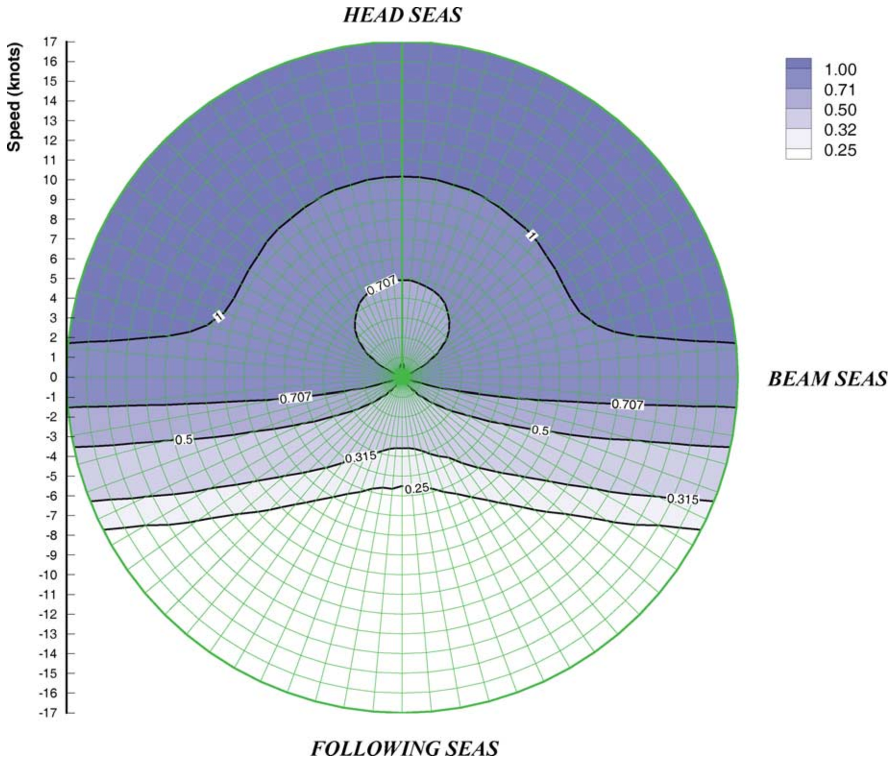

Fig. 7. Speed polar diagram of RMS vertical acceleration in sea state 6.

Table 2
Limiting criteria for vertical acceleration (Odabaşı et al., 1991)

Vertical RMS acceleration (g)	Description
0.020	Passengers on a cruise liner. Older people. Close to the lower threshold below which vomiting is unlikely
0.050	Passengers on a ferry. The international standard for 2 h exposure period. Causes symptoms of motion sickness in approximately 10% of unacclimatized adults
0.100	Intellectual work by people reasonably well adapted to ship motions (i.e. scientific personnel on ocean research vessels). Cognitive/manual work of a more demanding nature. Long term tolerable for the crew. The international standard for half an hour exposure period
0.150	Heavy manual work by people adapted to ship motions: for instance on fishing vessels and supply ships
0.200	Light manual work by people adapted to ship motions. Not tolerable for longer periods. Quickly causes fatigue
0.275	Simple light work. Most of the attention must be devoted to keeping balance. Tolerable only for short periods on high-speed craft

Table 3
Typical personnel performance criteria for warships

Application	Motion	Limit	Location
General	Vertical Acceleration	0.4 g	Bridge
	Lateral Acceleration	0.2 g	Bridge
Specific Task	MSI	20% of personnel	Task location
	MII	1/min	Task location

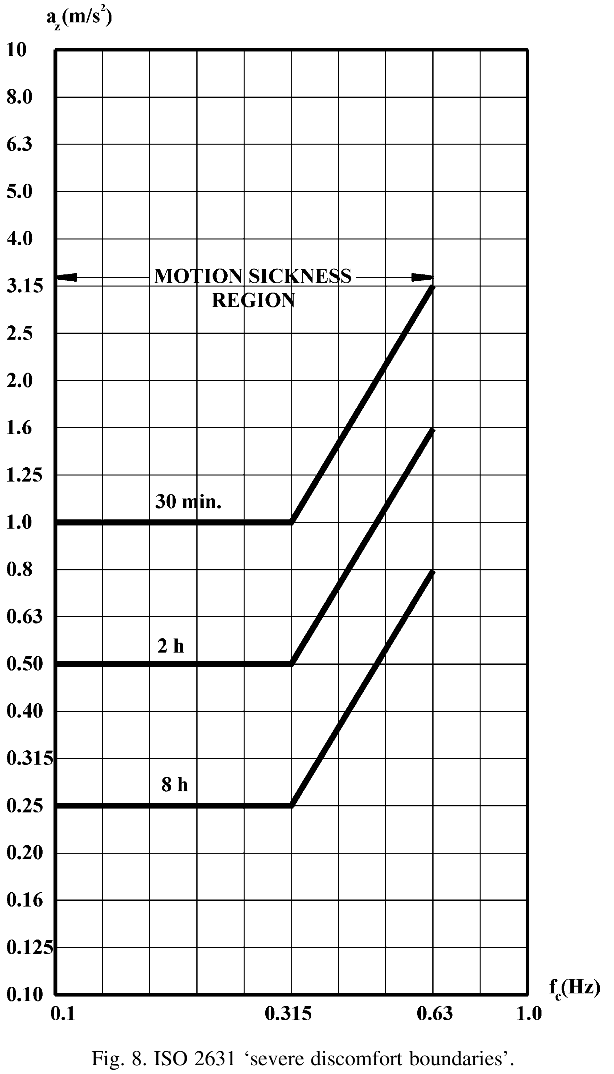

Fig. 8. ISO 2631 ‘severe discomfort boundaries’.

value can be calculated in the frequency domain. Implicit in the LFE concept is the assumption that the ship-referenced vertical acceleration is negligible; hence, the LFE is only a valid estimator of MIIs under conditions in which the vertical acceleration is small.

The main source of criteria on motion sickness is the International Standard ISO 2631 (ISO 2631-3, 1985). ISO standard 2631/3/1985 covers vertical vibration in the frequency range 0.1–0.63 Hz and links the factors of vertical acceleration, exposure time and frequency, and provides severe discomfort boundaries in terms of the RMS vertical acceleration for different exposure times as a function of the centre frequency of one-third octave band, as shown in Fig. 8. This forms an ideal basis for the analysis of motion sickness on ships.

Experimental observations indicate that the greatest sensitivity to vertical accelerations is in the range of 0.125–0.25 Hz with a rapid reduction in sensitivity at higher frequencies. Above 0.315 Hz, the severe discomfort boundary defined by ISO 2631/3 increases by the rate of 10 dB per octave.

The field data indicates that about 10% of the passengers will be seasick when the root mean square (RMS) acceleration is 0.5 m/s^2 (approximately 0.05 g significant) which is also the ISO-boundary for an exposure period of two hours in the frequency range 0.1–0.315 Hz.

As shown in Fig. 8, depending on exposure time and frequency of oscillation, different values of RMS vertical acceleration could be selected as seakeeping criteria. This would result in different levels of habitability for the same sea conditions. The effect of selected acceleration levels on habitability assessment is illustrated in the following section.

3. Habitability assessment

For each combination of speed, heading, and sea state, seakeeping performance can be assessed using the speed polar diagram concept. In the diagram a set of limiting criteria is used to define an area of ship speed and relative heading combinations within which particular missions can be executed without violating any of the limiting criteria. The ratio of the habitable area to the area of the polar plot defines an Habitability Index for the ship, seaway and sea state being considered.

In order to illustrate the effect of chosen criteria on habitability, the vertical accelerations at the passenger saloon were calculated for sea states 5 and 6 with corresponding significant wave height values of 3.25 and 5 m, respectively. Speed polar diagrams on the basis of different levels of RMS vertical accelerations, specified by ISO

Table 4
The selected levels of accelerations

Exposure time	RMS acceleration (m/s^2)
8 h	0.250
4 h	0.315
2 h	0.500
1 h	0.707
30 min	1.000

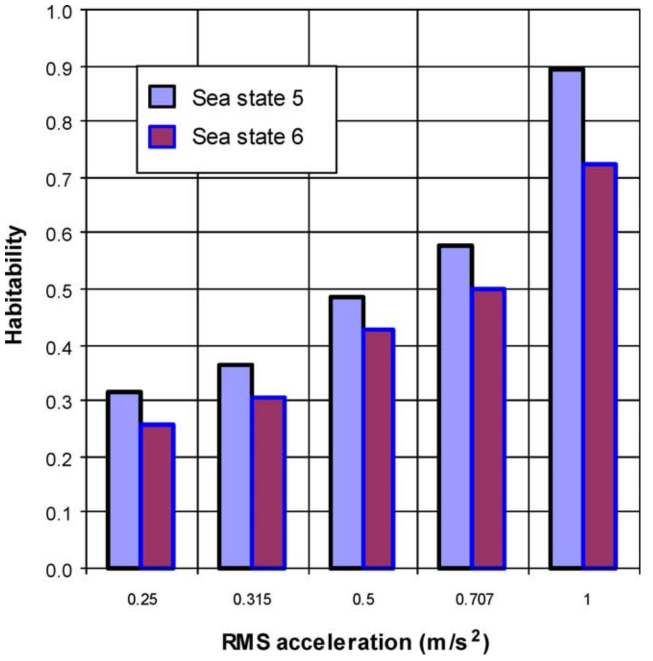

Fig. 9. Habitability indices as a function of selected limiting acceleration level.

2631 as a function of exposure time, are shown in Figs. 6 and 7. The selected levels of accelerations are defined in Table 4.

As shown in the speed polar diagrams the level of RMS vertical acceleration significantly affect the estimated habitability. For this vessel, in sea states 5 and 6, the estimated habitability based on vertical accelerations at passenger saloon are shown in Fig. 9.

4. Concluding remarks

The assessment of seakeeping performance of a vessel in a specified sea area is a common computational procedure for which a typical example is presented in this paper. This procedure requires the prediction of transfer functions for different speed and headings for each response. These transfer functions are then combined with an appropriate spectral formulation based on the sea area characteristics. The results are presented in a polar format where for each speed and heading combinations the variation of motion characteristics with increasing sea state can be established. Provided that a set of reliable seakeeping criteria are available the habitability of the vessel in different sea states can be estimated.

However, there are no universally agreed criteria for comparing the seakeeping performance of alternative designs. For passenger ships, the criteria are dominated by vertical and lateral accelerations. ISO 2631 provides 'severe discomfort boundaries' as a function of frequency and exposure time. The results indicate that even slight variations in exposure time may result in significant differences in estimated habitability. Hence, the methods currently used for comparing the seakeeping capabilities of ships can be misleading.

It is shown in the paper that, the estimated habitability of a passenger vessel in a specified sea area strongly depends on the selected limiting acceleration level. Therefore, particularly in comparative seakeeping analyses, the chosen set of criteria and its parameters must specifically be described in order to provide reliable seakeeping performance information.

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