MSI Analysis of a Roro Ferry Design

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Abstract: Crew and passengers' comfort is one of the main objectives in the design of a ferry. A parameter quantifying it is the so-called motion sickness incidence (MSI). In this study, the comfort level of a roro ferry design is assessed for which the vessel's vertical acceleration and the MSI were used as quantitative parameters. The voyage area is the seas around Adaut, Saumlaki and Letwurung in the Eastern part of Indonesia. The response characteristics of the vessel were calculated using a diffraction theory. The vertical acceleration and the MSI were determined from the vessel's relative motion. The predicted vertical acceleration is 1.18 m/s^2 or equal to 0.12 *g*, where *g* is the gravitational acceleration. Although the vertical acceleration is 20% below the maximum recommended one of 0.15 *g*, the discomfort level is, according to ISO 2631-1: 1997, classified as uncomfortable. Furthermore, the predicted MSI is approximately 15%, which is larger than the maximum recommended one of 10%. Further consideration of the design and/or operating location is recommended.

1 INTRODUCTION

Crew and passengers' comfort is one of the main objectives in the design of ferries. A parameter quantifying it is the so-called motion sickness incidence (MSI), which concept was first proposed by O'Hanlon and McCauley (1974) in the early 1970s. A definition of the MSI is as follows: the percentage of passengers who vomit within an exposure time of two hours. Improvement of comfort level and the consequence reduction of MSI have always been considered as the most important factors in the design of passenger ships (Campana et al., 2009; Diez and Peri, 2010).

Piscopo and Scamardella (2015) gives an overview of the historical development of the concept of MSI and the similar concept, called vomiting incidence (VI), developed by Lawther and Griffin (1987). The development started from a consideration of a simple vertical sinusoidal motion (O'Hanlon and McCauley, 1974) to irregular waves making an arbitrary angle to a moving vehicle, including population characteristics (age, gender). It turns out that the vessel's vertical acceleration dominantly determines the motion sickness incidence (O'Hanlon and McCauley, 1974; Lawther and Griffin, 1987; ISO, 1997; Lloyd, 1998; Cepowski, 2012; Piscopo and Scamardella, 2015).

The purpose of this study is to analyse a given ferry design regarding its comfort level by estimating the vessel's vertical acceleration and the value of the MSI, which are then compared with recommended standard values. The analysis results can serve as feedback to further consider the design and/or the operating location of the ferry.

Furthermore, case studies of full-scale design in which detail calculations of vertical acceleration and MSI are discussed, are still lacking. The present results can enrich the literature on MSI.

2 SHIP PARTICULARS AND WAVE DATA

The ship particulars are summarized in Table 1. The lines plan and general arrangement are shown in Figs. 1 and 2, respectively (Safiraa, 2017; Setyawan, 2018).

The intended operating location of the ferry is the seas around Adaut, Saumlaki and Letwurung in the Eastern part of Indonesia (see Figs. 3 and 4). The representative significant wave height is 2.28 m and the average zero up-crossing wave period is 5.95 s

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(BMKG, 2018). The wave spectrum calculated using the ITTC formulation (ITTC, 2002) is shown in Fig. 5.

Table 1: Ship Particulars.

Length overall	47.00 m
Length between perpendiculars	42.00 m
Breadth moulded	12.00 m
Depth	3.20 m
Draft	2.15 m
Volume of displacement	823.17 m^3
Service speed	12 knots
Crew	20 persons
Passenger	152 persons
Vehicle	12 trucks and 7 sedans
Main engine	2 x 800 HP Heavy duty

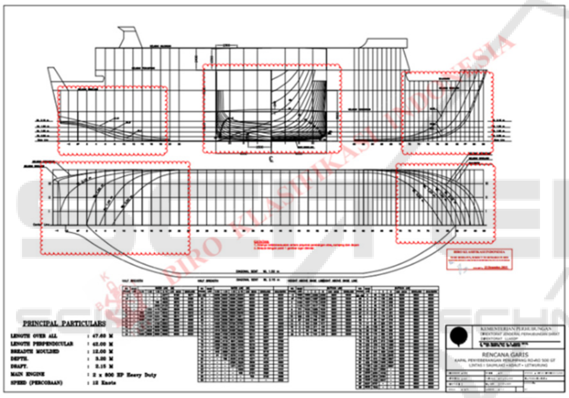

Figure 1: Lines plan of the roro ferry.

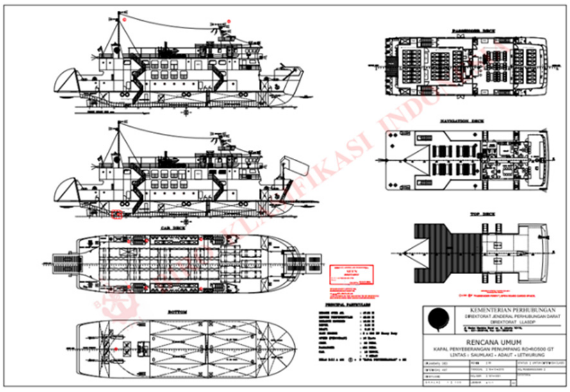

Figure 2: General arrangement of the roro ferry.

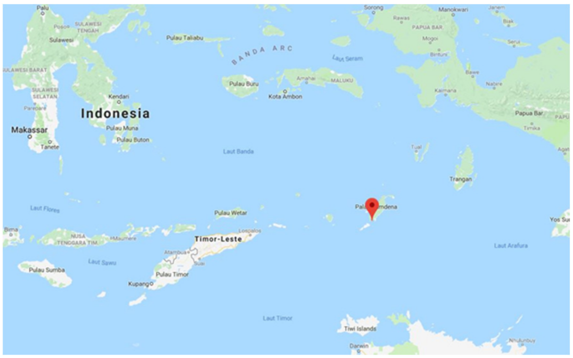

Figure 3: A map showing Banda seas, Arafura seas and Timor seas in the Eastern part of Indonesia in which Adaut, Saumlaki and Letwurung are located (marked with a red balloon).

Figure 4: The seas around Adaut, Saumlaki and Letwurung (zoomed in from Fig. 3).

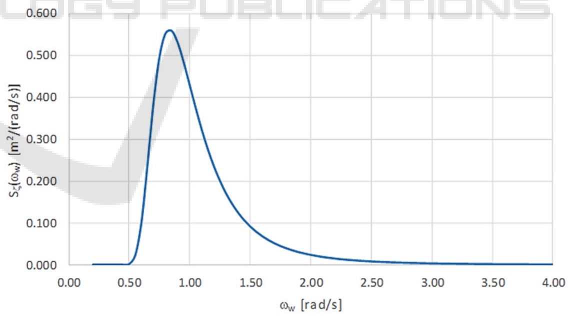

Figure 5: Representative wave spectrum for the seas around Adaut, Saumlaki and Letwurung.

3 PROCEDURE FOR THE MSI CALCULATION

A formula to calculate the MSI is given in Lloyd (1998) as follows:

$$\mathrm{MSI} = 100\left[0.5 + \mathrm{erf}\left(\frac{\log_{10}\left(0.798\sqrt{m_4}/g\right) - \mu_{\mathrm{MSI}}}{0.4}\right)\right] \quad (1)$$

where the parameter μ_{MSI}, according to O'Hanlon and McCauley (1974), is given as

$$\mu_{\mathrm{MSI}} = 0.654 + 3.697\log_{10}\left(\frac{1}{2\pi}\sqrt{m_4/m_2}\right) + 2.320\left[\log_{10}\left(\frac{1}{2\pi}\sqrt{m_4/m_2}\right)\right]^2 \quad (2)$$

while according to Lloyd (1998) given as

$$\mu_{\mathrm{MSI}} = -0.819 + 2.32\left[\log_{10}\left(\sqrt{m_4/m_2}\right)\right]^2 \quad (3)$$

In Eqs. (1), (2) and (3), erf is the error function, m_2 and m_4 are, respectively, the second and fourth spectral moments of the relative motion spectrum [see Eq. (11) below] and g is the gravitational acceleration.

As has been stated earlier in the introduction, the main contributor to MSI is the vessel's vertical acceleration. This manifests in Eq. (1) in which the quantity $\sqrt{m_4}$ represents a measure for the vessel's vertical acceleration.

Due to the ship speed and its relative direction to the wave propagation direction, the wave frequency is Doppler shifted, represented by the encounter wave frequency as follows (Bhattacharyya, 1978):

$$\omega_e = \omega_w - \frac{\omega_w^2 V}{g}\cos\mu \quad (4)$$

(for deep water) where ω_e is the encounter wave frequency, ω_w is the wave frequency relative to the fixed bottom, g is the gravitational acceleration, V is the ship speed and μ is the wave heading ($\mu = 90^\circ$ for beam seas and $\mu = 180^\circ$ for head seas). Correspondingly, the encounter wave spectrum is given as

$$S_\zeta(\omega_e) = S_\zeta(\omega_w)\frac{1}{\sqrt{1-\left(\frac{4\omega_e V}{g}\right)\cos\mu}} \quad (5)$$

where $S_\zeta(\omega_e)$ is the encounter wave spectrum and $S_\zeta(\omega_w)$ is the wave spectrum for zero-speed ship. In this study, the wave headings considered are from beam seas to head seas.

Figure 6 shows encounter wave spectra for 12 knots ship speed with 90º, 135º and 180º wave headings. For $\mu = 90^\circ$, $\omega_e = \omega_w$ and $S_\zeta(\omega_e) = S_\zeta(\omega_w)$, as expected, because cos $\mu = 0$ in this case (cf. Fig. 5). As μ increases from 90º to 180º, the spectral peak decreases but the frequency range with significant wave energy becomes wider. The areas under the spectral energy curves remain constant, that is, the energy content of the wave field remains unaltered.

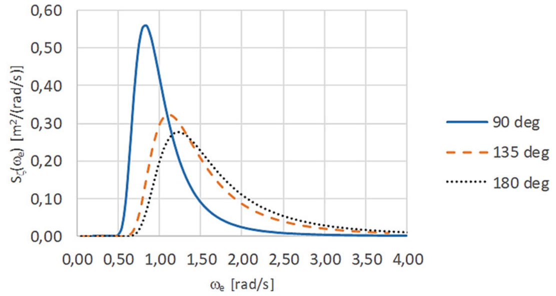

Figure 6: Encounter wave spectra for 12 knots ship speed with 90º, 135º and 180º wave headings.

The response characteristics of the vessel are represented by the response amplitude operators (RAO). Only the heave and pitch motions are considered in the present study. The motion RAOs are calculated using a diffraction theory (Newman, 1977).

Figures 7 and 8 show the heave and pitch RAOs, respectively, as function of encounter wave frequency for 12 knots ship speed with 90º, 135º and 180º wave headings. The wave heading $\mu = 180^\circ$ (head seas) gives the largest heave and pitch responses, followed by $\mu = 135^\circ$ and subsequently by $\mu = 90^\circ$ (beam seas).

Laying down Figs. 7 and 8 aside Fig. 6, it is observed that a significant response of the ship for $\mu = 135^\circ$ and 180º occurs in the frequency range where significant wave energy is present ($0.8 < \omega_e < 1.8$ rad/s). The heave RAO can reach approximately 1.2 m/m and the pitch RAO can reach 5º/m. Because of the above situation, relatively large ship responses can be expected, particularly for the condition of head seas.

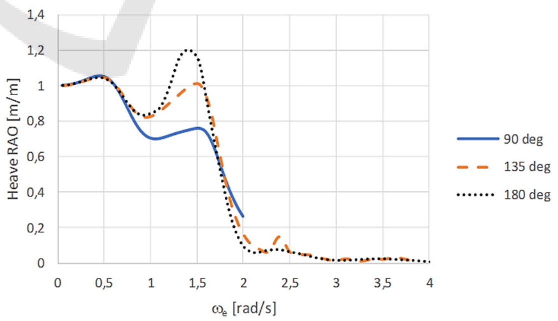

Figure 7: Heave RAOs for 12 knots ship speed with 90º, 135º and 180º wave headings.

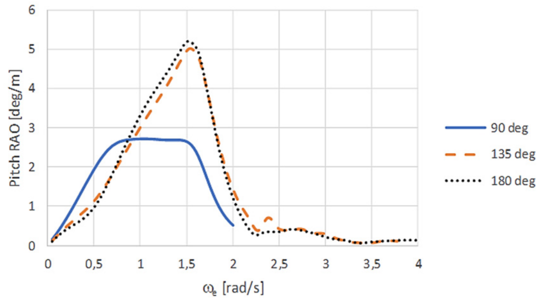

Figure 8: Pitch RAOs for 12 knots ship speed with 90º, 135º and 180º wave headings.

In the following, all calculations are based on the encounter wave frequency ω_e. Utilizing the RAO and the wave spectrum, the heave and pitch spectra of the vessel can be calculated as follows (Bhattacharyya, 1978):

$$S_R(\omega_e) = [\text{RAO}\ (\omega_e)]^2 S_\varsigma(\omega_e) \quad (6)$$

where $S_R(\omega_e)$ is the response spectrum and $S_\varsigma(\omega_e)$ is the wave spectrum. Figures 9 and 10 show the heave and pitch spectra, respectively, for 12 knots ship speed with 90º, 135º and 180º wave headings. The significant response amplitude A_s is used as a parameter to characterize the motion spectra, which is calculated as follows:

$$A_s = 2\sqrt{m_0} \quad (7)$$

where m_0 is the area under the response spectrum. Using Eq. (7), the significant heave amplitudes are, respectively, 0.868, 0.877 and 0.897 m for μ = 90º, 135º and 180º. Furthermore, the significant pitch amplitudes are, respectively, 2.94º, 3.82º, and 3.96º for μ = 90º, 135º and 180º. The wave heading μ = 180º (head seas) gives the largest heave and pitch responses, as expected (in view of the heave and pitch RAOs described above).

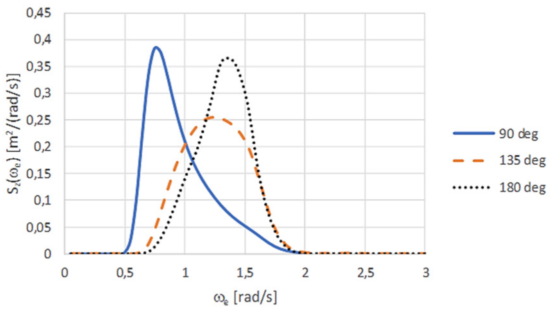

Figure 9: Heave spectra for 12 knots ship speed with 90º, 135º and 180º wave headings.

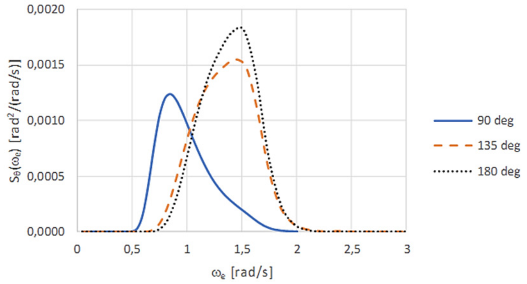

Figure 10: Pitch spectra for 12 knots ship speed with 90º, 135º and 180º wave headings.

In the following, only results for wave heading μ = 180º (head seas) are presented because it gives the largest responses.

Utilizing the heave and pitch spectra, the relative motion spectrum can be calculated from the following relation (Bhattacharyya, 1978):

$$S_s(\omega_e) = S_z(\omega_e) + [xS_\theta(\omega_e)] - S_\varsigma(\omega_e) \quad (8)$$

where $S_s(\omega_e)$ is the relative motion spectrum, $S_z(\omega_e)$ the heave spectrum, $S_\theta(\omega_e)$ is the pitch spectrum, $S_\varsigma(\omega_e)$ is the wave spectrum and x is the longitudinal distance from the centre of gravity (CG) to the point under consideration. The longitudinal centre of gravity (LCG) of the ferry is 18.51 m measured from the aft perpendicular. Its vertical distance from the base line (VCG) is 2.15 m. Notice in Figs. 9 and 10 that for ω_e > 2.0 rad/s, both $S_z(\omega_e)$ and $S_\theta(\omega_e)$ tend to zero. So, Eq. (8) becomes $S_s(\omega_e) = -S_\varsigma(\omega_e)$ for ω_e > 2.0 rad/s. This observation will be used to check the resulting relative motion spectrum.

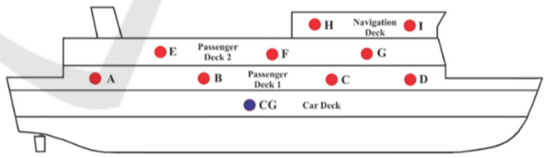

Figure 11: Locations within the ship where the relative motion, the vertical acceleration and the MSI are calculated, denoted by points A, B, … I.

Some locations have been chosen within the ship where the relative motion, the vertical acceleration and the MSI are calculated (see Fig. 11). For example, Fig. 12 shows the relative motion spectrum at point I (front navigation deck). The relative motion spectrum can take negative and positive values. Looking at Figs. 12 and 6, it is observed that $S_s(\omega_e) = -S_\varsigma(\omega_e)$ for ω_e > 2.0 rad/s, as has been anticipated.

Based on the relative motion spectrum, the velocity spectrum and the acceleration spectrum can be calculated as follows:

$$S_v(\omega_e) = \omega_e^2 S_s(\omega_e) \quad (9)$$

$$S_a(\omega_e) = \omega_e^4 S_s(\omega_e) \quad (10)$$

where $S_v(\omega_e)$ is the velocity spectrum and $S_a(\omega_e)$ is the acceleration spectrum. Figure 13 shows the acceleration spectrum at point I for 12 knots ship speed in head seas, calculated using Eq. (10). The values of the acceleration spectrum at relatively high frequencies become dominated by the factor ω_e^4. For example, at $\omega_e = 4.5$ rad/s, the (absolute) value of the motion spectrum is much smaller than the peak value (Fig. 12) but the (absolute) value of the acceleration spectrum at this frequency takes the largest value (a global maximum) due to the factor ω_e^4. This value may not be reliable. Therefore, care should be taken in interpreting the acceleration spectrum. Furthermore, at $\omega_e = 3.0$ rad/s, the value of the wave spectrum is approximately 10% of the peak value (Fig. 6 for $\mu = 180^o$) and the values of the heave and pitch spectra are approximately zero for $\omega_e > 2.0$ rad/s (Figs. 9 and 10). Therefore, for the calculation of the significant amplitude of the acceleration, the acceleration spectrum will be truncated at $\omega_e = 3.0$ rad/s, that is, the spectral values for $\omega_e > 3.0$ rad/s will be neglected.

To calculate the significant amplitudes of the velocity and acceleration, it is common to define a spectral moment m_n as follows:

$$m_n = \int_0^\infty \omega_e^n \, S_s(\omega_e) \mathrm{d}\omega_e, n = 0,1,2 \ldots \quad (11)$$

Using the definition in Eq. (11), m_0 is the area under the relative motion spectrum (in m^2), m_2 is the area under the relative velocity spectrum (in m^2/s^2) and m_4 is the area under the acceleration spectrum (in m^2/s^4). The significant amplitude of the vertical acceleration is required for the calculation of the MSI and to determine the discomfort level of the ferry. In Eq. (1), the significant amplitude of the vertical acceleration is calculated as $0.798\sqrt{m_4}$.

4 RESULTS AND DISCUSSION

Figure 14 shows the vertical acceleration spectra at points F (1.0 m fore CG), H (2.0 m fore CG) and I (12.0 m fore CG) for 12 knots ship speed in head seas (truncated at $\omega_e = 3.0$ rad/s). As shown in Fig. 14, the three curves almost coincide. This observation holds also for all other points shown in Fig. 11. This indicates that the longitudinal distance x from the point under consideration to CG [or the second term in the r.h.s. of Eq. (8)] does not contribute significantly to the resulting motion spectrum (acceleration spectrum). In other words, the pitch response plays a minor role compared to the heave response in determining the relative motion (vertical acceleration) of the vessel.

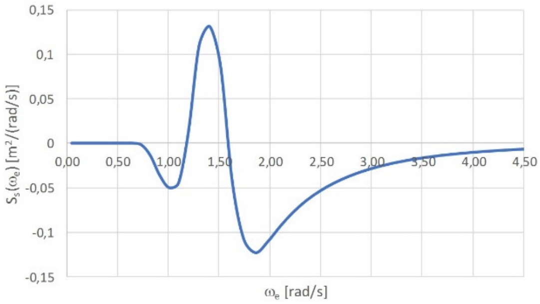

Figure 12: Relative motion spectrum at point I for 12 knots ship speed in head seas.

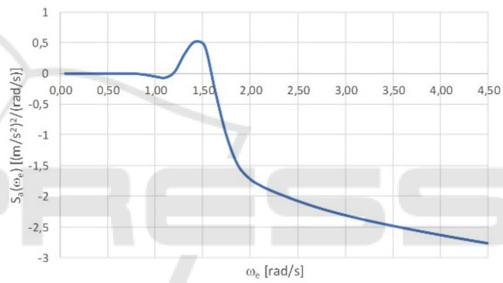

Figure 13: Vertical acceleration spectrum at point I for 12 knots ship speed in head seas.

The acceleration amplitude calculated as $0.798\sqrt{m_4}$ is approximately 1.18 m/s^2 or equal to 0.12 g, where g is the gravitational acceleration. The recommended maximum vertical acceleration is 0.15 g (Bhattacharyya, 1978). Although the predicted vertical acceleration is 20% below the recommended maximum value of 0.15 g, the discomfort level is, according to ISO 2631-1: 1997 [see Table 2], classified as *uncomfortable*.

The MSI calculated from Eqs. (1) and (2) is 14.63% and that calculated from Eqs. (1) and (3) is 14.51%. They are close to each other, which can be rounded to 15%. The predicted MSI of 15% is larger than the maximum recommended one of 10% (ISO, 1997; Kivimaa et al., 2014).

Based on the predicted vertical acceleration and the MSI, it is recommended to further consider the present design to make the vessel more comfortable for crew and passengers if the ferry is to be operated in the seas around Adaut, Saumlaki and Letwurung. Another option is, if modifications are difficult to achieve, the ferry should be operated in other locations where the wave condition is more favourable.

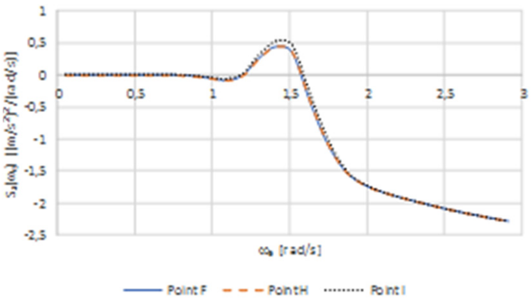

Figure 14: Vertical acceleration spectra at points F (1.0 m fore CG), H (2.0 m fore CG) and I (12.0 m fore CG) for 12 knots ship speed in head waves (truncated at $\omega_e = 3.0$ rad/s).

Table 2: Classification of discomfort level (ISO, 1997).

Habitability Acceleration	Discomfort Response
< 0,315 m/s^2	Not uncomfortable
0,315 – 0,63 m/s^2	A little uncomfortable
0,5 – 1 m/s^2	Fairly uncomfortable
0,8 – 1,6 m/s^2	Uncomfortable
1,25 – 2,5 m/s^2	Very uncomfortable
> 2 m/s^2	Extremely uncomfortable

5 CONCLUSIONS

The comfort level for crew and passengers of a ferry design was analysed for which the vessel's vertical acceleration and the MSI were estimated using a standard procedure. The predicted vertical acceleration is 1.18 m/s^2 or equal to 0.12 g, where g is the gravitational acceleration. Although the vessel's vertical acceleration is 20% below the maximum recommended one of 0.15 g, the discomfort level is, according to ISO 2631-1: 1997, classified as uncomfortable. Furthermore, the predicted MSI is approximately 15%, which is larger than the maximum recommended one of 10%. It is recommended to further consider the present design to make the vessel more comfortable for crew and passengers if the ferry is to be operated in the seas around Adaut, Saumlaki and Letwurung in the Eastern part of Indonesia. If modifications of the design are difficult to achieve, then the ferry should be operated in other locations where the wave condition is more favourable.

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REFERENCES

A. Lawther, M. J. Griffin, 1987. Prediction of the incidence of motion sickness from the magnitude, frequency and duration of vertical oscillation, J. Acoustical Soc. America 82 (3), pp. 957-966.
A. R. J. M. Lloyd, 1998. Seakeeping: Ship behaviour in rough water, Ellis Horwood Ltd.
BMKG, 2018. Indonesian Agency for Meteorology, Climatology and Geophysics.
D. Safiraa, 2017. Undergraduate Thesis (in Indonesian), Department of Naval Architecture, Faculty of Marine Technology, ITS Surabaya, Indonesia.
E. F. Campana, G. Liuzzi, S. Lucidi, D. Peri, V. Piccialli, A. Pinto, 2009. New global optimization methods for ship design problems, Optimization Engrg. 10 (4), pp. 533-555.
H. Setyawan, 2018. Undergraduate Thesis (in Indonesian), Department of Naval Architecture, Faculty of Marine Technology, ITS Surabaya, Indonesia.
ISO, 1997. Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements, Int'l. Organization Standardization.
ITTC, 2002. Proc. 23rd Int'l Towing Tank Conf.
J. F. O'Hanlon, M. E. McCauley, 1974. Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion, Aerospace Medicine 45 (4), pp. 366-369.
J. N. Newman, 1977. Marine hydrodynamics, The MIT Press.
M. Diez, D. Peri, 2010. Robust optimization for ship conceptual design, Ocean Engrg. 37 (11-12), pp 966-977.
R. Bhattacharyya, 1978. Dynamics of marine vehicles, Wiley.
S. Kivimaa, A. Rantanen, T. Nyman, D. Owen, T. Garner, B. Davies, 2014. Ship motions, vibration and noise influence on crew performance and well-being studies in FAROS project, Transport Research Arena (TRA) 5th Conf.: Transport Solutions from Research to Deployment, Paris.
T. Cepowski, 2012. The prediction of the motion sickness incidence index at the initial design stage, Zeszyty Naukowe 31 (103), pp. 45-48.
V. Piscopo, A. Scamardella, 2015. The overall motion sickness incidence applied to catamarans, J. Nav. Archit. Ocean Engrg. 7, pp. 655-669