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Research Article

Vulnerability Assessment for Excessive Acceleration Failure Mode of an Indonesian Ro-Ro Ferry by Model Experiment

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Abstract: The Indonesian ro-ro ferries have a large breadth-to-draught ratio and metacentric height. The passenger and crew accommodations are located at a significantly higher position from the roll axis because the main deck is used as a vehicle deck. The damping factor corresponding to criteria levels 1 and 2 of the excessive acceleration failure mode given by the International Maritime Organization (IMO) may not be applied to the Indonesian ro-ro ferry due to the large breadth-to-draught ratio and the ratio between the distance of the center of gravity from the sea surface and ship draught. An alternative method to determine the damping factors becomes important in applying the criteria for the Indonesian ro-ro ferries. The roll decay test is used as the alternative method to estimate the non-dimensional logarithmic decrement of roll decay and the damping coefficients to assess the stability base on the excessive acceleration criteria. The long-term probability index corresponding to the criteria level 2 is calculated by using the limited scatter wave of IMO. The non-dimensional logarithmic decrement of roll decay obtained by the model experiment is smaller than that obtained by the formula of IMO when the roll angle is smaller than 17.45 degrees. The bilge keels significantly reduce the long-term probability index. As a result, the ship complies with the criteria for excessive acceleration failure mode, even though the height of the accommodations from the roll axis is greater than 80% of the ship breadth and the significant wave height is greater than 7.5 meters.

Keywords: Damping factor; Excessive acceleration; Model experiment; Ro-Ro ferry; Stability

1. Introduction

Shifting or overthrowing a vehicle is a frequent accident in Indonesian ro-ro ferries (Mahendra, 2019; Fanani, 2019). The accidents occur in ro-ro ferries (KMP Gerbang Samudera II and KMP Pelangi Nusantara) operated in Bali Strait to connect Ketapang (East Java) and Gilimanuk (Bali) of Indonesia. The meteorological, climatological, and geophysical agencies predicted a wave height of higher than 2 meters. Ships experience a significant roll angle that causes the lashing of large trucks on the vehicle deck to damage and overturn to the ship side. A large lateral force may be induced by coupled motions of the ships. Paroka et al. (2017) showed that the surge and yaw motions of an

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Indonesian ro-ro ferry could be significant under the combined action of wind and waves depending on the direction relative to the ship. A similar results corresponding to the lateral motions has been found due to action of wind (Paroka, 2020). The Indonesian ro-ro ferry can operate in many wind and wave directions due to its route characteristics (Muhammad et al., 2021) and the hydrodynamics forces and moment correspond to sway and yaw motion should be accurately estimated (Sunarsih et al, 2023).

Shigunov et al. (2011) identified that a shifting car or cargo onboard a vessel might occur due to a large roll angle which can induce a significant lateral acceleration. The International Maritime Organization (IMO) included lateral acceleration as one of the failure modes on ship stability in the Second Generation Intact Stability Criteria (SGISC), called the excessive acceleration failure mode. The SGISC was finalized in February 2020, and the Maritime Safety Committee approved its Interim Guidelines by the end of the same year (IMO, 2020). A ship with a metacentric height (GM) larger than 8% of the ship breadth and the height of accommodations from the roll axis larger than 70% of the ship breadth should be tested against the excessive acceleration criteria (Pettaco and Gualeni, 2020; Boccadamo and Rosano, 2019).

Most Indonesian ro-ro ferries have a GM larger than 8% of ship breadth. Indeed, an Indonesian ro-ro ferry has a GM of 36.3% of the ship's breadth (Paroka et al., 2020). A ship with a large breadth-to-draught ratio has a large metacentric radius. Therefore, the GM becomes large even if the ship has a large vertical center of gravity. The passenger and crew accommodations are located in a high position above the car deck. As a result, Indonesian ro-ro ferries may be vulnerable to excessive acceleration failure mode. The shifting or overthrowing of vehicles on the car deck showed that a significant lateral acceleration could occur even if the vertical distance from the roll axis is smaller than 70% of the ship breadth when the GM is larger than 8% of the ship breadth. The natural roll period of Indonesian ro-ro ferries can be smaller than 6 seconds. Shin and Moon (2022) found that the small natural roll period can make the ship vulnerable to excessive acceleration failure mode. Yang (2023) showed that the excessive acceleration sensitive against the alteration of natural roll period. This means that the metacentric height and the roll radius gyration have significant effect to the excessive acceleration.

IMO has given the formula for calculating the vulnerability index of the criteria at each level (IMO, 2015a). In the vulnerability criteria level 1, the non-dimensional logarithmic decrement of roll decay is determined based on the midship coefficient and the bilge keel dimensions. IMO recommended the simplified method of Ikeda to estimate the damping coefficients for vulnerability criteria level 2. However, this method is valid only for a ship with a breadth-to-draught ratio between 2.5 and 4.5 and the ratio between the distance of the center of gravity from the water surface (OG) and the ship draught between -1.5 and 0.2 (IMO, 2019a). Duan et al. (2022) showed that the Rankine Panel method gives more accurate results than the method recommended by IMO. Most Indonesian ro-ro ferries have a breadth-to-draught ratio larger than 4.5 and a ratio between OG and draught larger than 1.6 (Paroka et al., 2021). Therefore, the simplified Ikeda's method cannot be applied to Indonesian ro-ro ferries. Experiment results showed that the non-dimensional logarithmic decrement of roll decay obtained using the formula recommended by IMO overestimates.

To apply the excessive acceleration criteria to an Indonesian ro-ro ferry, an alternative method to determine the non-dimensional logarithmic decrement of roll decay and the damping coefficients become important. Irkal et al. (2019) used a numerical approach to estimate the effect of bilge keels on the damping coefficient of a ship. Their results indicate that the accuracy of the numerical method depends on the meshing method and bilge keel dimensions. IMO (2006) proposed a guideline to estimate the damping coefficients and the effective wave slope coefficient for dead ship failure mode using model experiments. Those model experiments may be used in the excessive acceleration criteria because variables in the formula to calculate the non-dimensional logarithmic decrement of roll decay can be determined based on the results of the roll decay test (IMO, 2015b). The damping coefficients to calculate the non-dimensional decrement of roll decay can be determined using some available methods, such as ITTC (2011) and Fernandes and Oliveira (2009).

The formula recommended by the IMO and Ikeda's simplified procedure has been used to assess excessive acceleration criteria for ships with breadth-to-draught ratio smaller than 4.5 (Shin and Moon, 2022; Begovic et al., 2022; Pettaco and Gualeni, 2020; Boccadamo and Rosano, 2019; IMO, 2019b). Therefore, an alternative method to estimate the damping factor becomes important when applying the excessive acceleration criteria to vessels with a breadth-to-draught ratio larger than 4.5 and having a significant vertical center of gravity, like Indonesian ro-ro ferries. This paper discusses the stability assessment of an Indonesian ro-ro ferry against the excessive acceleration criteria with damping factors determined based on a model experiment. The results may be used to verify the applicability of the criteria to a ship with geometric characteristics similar to Indonesian ro-ro ferries. This testing is essential because an extensive range of ship types and dimensions is necessary before the criteria included in Part A of the 2008 Intact Stability Code. On the other hand, operational limitations or guidance for the Indonesian ro-ro ferry can be developed as the operational location can be changed depending on the government policy.

2. Excessive Acceleration Criteria of SGISC

The excessive acceleration criteria aim to prevent significant lateral acceleration caused by roll motion when a ship operates in rough seas. The SGISC was developed with multiple layers of vulnerability against stability failure modes. If a ship does not meet the criteria of level 1, it should be tested against the criteria of level 2. If a ship cannot meet the criteria of level 2, a direct assessment is necessary, and an operational measurement should be developed, such as operational limitation or operational guidance. Kuroda et al. (2018) conducted a direct assessment using numerical codes in the frequency domain and time domain, which were validated by a model experiment for a container ship.

2.1. Criteria Level 1

A ship is supposed to be vulnerable against criteria level 1 in a specific loading condition if the condition shown in equation (1) is fulfilled (IMO, 2020).

$$\varphi . k_L . \left(g + 4\pi^2 h_r / T_r{}^2\right) \geq 4.64\ (m/s^2) \tag{1}$$

Where φ is the characteristic roll amplitude in radian, k_L is the factor due to the simultaneous action of roll, yaw and pitch motions. g is the gravitational acceleration. h_r and T_r are the height of the considered location of the passenger or crew from the roll axis and the natural roll period, respectively. The characteristic roll amplitude is calculated by using equation (2).

$$\varphi = \frac{4.43 \cdot r \cdot s}{\delta_\varphi{}^{0.5}} \tag{2}$$

Here, r is the effective wave slope coefficient, s is the wave steepness, and δ_φ is the non-dimensional logarithmic decrement of roll decay which is calculated as a function of the bilge keel area and the length and the breadth of the ship (IMO, 2020). Alternatively, the non-dimensional logarithmic decrement of roll decay can be calculated by using the equation as follows (IMO, 2015b):

$$\delta_\varphi = 2 \cdot \pi \cdot \zeta \tag{3}$$

where

$$\zeta = \frac{\omega_\varphi \cdot B_\varphi}{2 \cdot g \cdot GM \cdot \Delta} \tag{4}$$

Here, ω_φ and B_φ are the natural frequency and the equivalent damping moment of roll, respectively. Δ indicates the ship displacement. There are several methods to calculate the damping moment, namely Ikeda's simplified method as recommended by IMO for the SGISC (IMO, 2019a), numerical simulation like CFD (Irkal et al., 2015; Yang et al., 2012) and model experiment (Oliveira et al., 2018; Irkal et al., 2014; Fernandes and Oliveira, 2009). The damping moment can be calculated by using the equation as follows (IMO, 2019a):

$$\frac{B_{\varphi}(\varphi_a)\cdot{\omega_{\varphi}}^2}{2\cdot g\cdot\Delta\cdot GM}=\delta_0+\frac{4}{3\cdot\pi}\cdot\delta_1\cdot\varphi_a+\frac{3}{8}\cdot\delta_2\cdot{\omega_{\varphi}}^2\cdot{\varphi_a}^2 \quad (5)$$

where δ_0, δ_1 and δ_2 are the linear, quadratic, and cubic damping coefficients, respectively. φ_a is the corresponding roll amplitude.

2.2. *Criteria Level 2*

A ship is considered vulnerable against the criteria level 2 if the condition in equation (6) is met (IMO, 2015a). In the equation, W_i represents the weighting factor of a pair of significant wave heights and mean wave period while $C_{s,i}$ denotes the short-term failure index corresponding to the pair of significant wave height and mean wave period.

$$\sum_{i=1}^{N} W_i\cdot C_{s,i}\geq 0.00039 \quad (6)$$

The short-term failure index is calculated by using the following equation:

$$C_{s,i}=exp\left(-\frac{{R_2}^2}{(2\cdot{\sigma_{LAi}}^2)}\right) \quad (7)$$

where R_2 is a specified lateral acceleration decided to be the same as the gravitational acceleration. σ_{LAi} is the standard deviation of the lateral acceleration at zero speed in beam seas, which can be calculated as follows:

$${\sigma_{LAi}}^2=\frac{3}{4}\sum_{j=1}^{N}\left(a_y(\omega_j)\right)^2\cdot S_{zz}(\omega_j)\cdot\Delta\omega \quad (8)$$

Here, $S_{zz}(\omega_j)$ is the sea wave elevation spectrum. The IMO recommended the Bretschneider wave energy spectrum. The other spectrum may be used depending on the wave characteristic of the operational area. ω_j and $\Delta\omega$ are the wave frequency at the mid-point of the considered frequency interval and the interval of wave frequency, respectively. a_y is the lateral acceleration depending on the location and the roll motion.

3. Model Experiment Set Up

An Indonesian ro-ro ferry was used as a sample ship. The principal dimension of the ship and the model are shown in Table 1. The model scale was 1 : 40.

Table 1 Principal dimension of the ship.

Dimension	Ship	Model
Length between perpendiculars (L_{BP})	47.25 m	1181.25 mm
Breadth (B)	13.00 m	325.00 mm
Height (H)	3.45 m	86.25 mm
Draught (T)	2.45 m	61.25 mm
Vertical center of gravity (VCG)	4.00 m	100.00 mm
Height of passenger accommodation (h_p)	5.96 m	149.00 mm
Height of crew accommodation (h_c)	6.65 m	166.25 mm
Length of bilge keels (l_{BK})	25.50 m	637.50 mm
Breadth of bilge keels (b_{BK})	0.25 m	6.25 mm

The breadth-to-draught ratio of the ship is 5.31, and the ratio between the distance of the center of gravity from the water surface and the draught is 0.63. The longitudinal position of passenger accommodations is 6.65 meters to 39.65 meters from the after perpendicular. The crew accommodation is located above the passenger accommodation with a longitudinal position of 27.26 meters to 41.49 meters from the after perpendicular. Most of the Indonesian ro-ro ferries have similar accommodation arrangements, mainly those built in Indonesian.

The roll moment of inertia was determined using the radius gyration coefficient and was found to be the same as that obtained by the formula provided in the weather criterion (IMO, 2008). Although the moment of inertia of a ro-pax ship may be larger than that obtained by the weather criterion formula (Kruger and Kluwe, 2008), the Indonesian ro-ro ferry was designed with a truck located around the centerline and small cars located near the ship's side. As a result, the roll moment of inertia of the Indonesian ro-ro ferry may be smaller than that given by Kruger and Kluwe (2008). The experiment was conducted in the towing tank of Hasanuddin University with a length of 60 meters, wide of 4 meters and a depth of 6 meters. The roll angle is measured using a dual-axis inclinometer located in the centerline at the midship of ship model. The inclinometer is connected to computer for recording the roll angle during decay. During the experiment, the model is free in 6 degrees of freedom (6 DOF) motion. The rope to restrain the yaw motion is released for roll decay. Firstly, the model is inclined with an angle of 25 degrees as the initial angle for roll decay by putting down the ship's side (starboard or portside). The model is released to perform roll motion, and the roll angle is recorded up to the angle of 0.5 degrees in the time domain, as shown in Figure 1. The roll decay test was run five times for the model without and with bilge keel, respectively. The linear dan quadratic damping coefficients of every running are determined using the method used by Fernandes and Oliveira (2009). Here, the linear and quadratic damping coefficients are determined based on the regression equation as follows:

$$\frac{2}{T_r} \cdot ln\left(\frac{\varphi_i}{\varphi_{i+1}}\right) = \delta_0 + \frac{8}{3 \cdot \pi} \cdot \omega_\varphi \cdot \varphi_m \cdot \delta_1 \quad (9)$$

where $\boldsymbol{\varphi_i}$ and $\boldsymbol{\varphi_{i+1}}$ are the two consecutive roll amplitudes, and $\boldsymbol{\varphi_m}$ is the average of two successive amplitudes of decayed roll motion. Finally, the logarithmic decrement of roll decay and the damping coefficients are determined as the average of the number of running of roll decay. The natural roll period is also calculated as the average of 5 running experiments.

4. Results and Discussion

The roll decay test of the subject ship with bilge keel is shown in Figure 1, and the linear and quadratic damping coefficients are shown in Figure 2, respectively. Those damping coefficients are used to conduct the roll decay test numerically, with results shown as the black line in Figure 1. The results are not significantly different. The non-dimensional logarithmic decrement of roll decay is calculated using equations (3) – (5), and the results are shown in Figure 3.

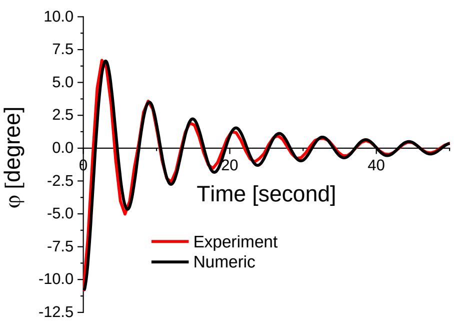


Figure 1 Results of roll decay test

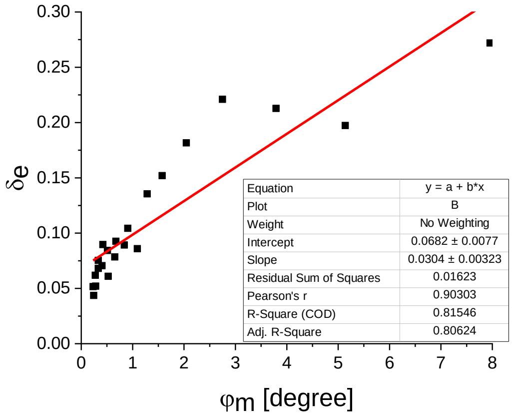


Figure 2 The linear and quadratic damping coefficients

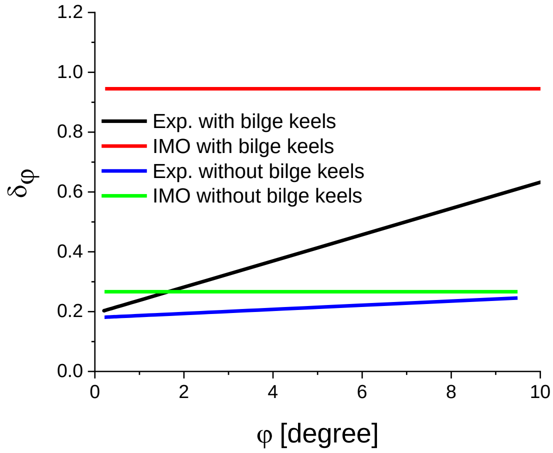


Figure 3 The non-dimensional logarithmic decrement of roll decay

The non-dimensional logarithmic decrement of roll decay obtained from the model experiment is lower than that calculated using the formula provided by IMO when the roll angle is less than 17.45 degrees for the subject ship equipped with bilge keels. For the same ship without bilge keels, the roll angle corresponding to the result from the model experiment being the same as the IMO formula is 12.57 degrees. While the effect of bilge keels is minimal for small roll amplitudes, their contribution increases as the roll amplitude grows. The vulnerability index for criteria level 1 is shown in Figure 4(a). Here, the non-dimensional logarithmic decrement of roll decay was determined by the model experiment at the heel angle of 20 degrees. For ships with geometric characteristics that differ from the subject ship, the assumed heel angle to calculate the non-dimensional logarithmic decrement of roll decay could be different. The subject ship is in full loading condition with the effective wave slope coefficient and wave steepness based on IMO procedures (IMO, 2020). The maximum GM for the subject ship complies with the criteria level 1 corresponding to the vertical distance from the roll axis is shown in Figure 4(b). The GM was, corresponding to the height from the roll axis of 70% of the ship's breadth is 1.305 meters (11.65% of the ship's breadth). This GM is larger than the requirement of IMO (8% of ship breadth), but it is smaller than the design GM of the subject ship in full loading condition. To comply with the vulnerability criteria level 1, the subject ship should be designed with accommodations for passengers and crew located at the lower position to reduce the vertical distance from the roll axis. However, reducing the vertical distance of accommodations will decrease the vertical center of gravity or increase the GM, which also significantly contributes to the excessive acceleration failure mode.

The vertical distance from the roll axis complies with the vulnerability criteria level 1 in the full loading condition is smaller than 2.6 meters (20% of ship breadth), as shown in Figure 4(b). These results indicate that the vehicle deck of the subject ship may experience a large lateral acceleration. The cars should be handled to avoid shifting or overthrowing during the ship operation. The wave steepness corresponding to the natural roll period is 0.1. This wave steepness overestimates when it is applied to Indonesian seas (Kurniawan et al., 2023 Paroka, 2014).

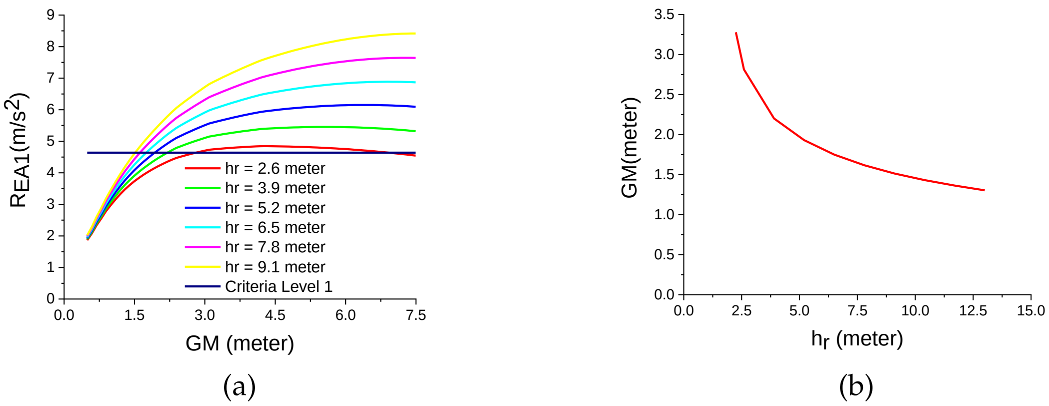


Figure 4 Vulnerability criteria level 1: (a) Failure index; (b) Limitation of GM for variation of vertical distance from the roll axis

The vulnerability index for the criteria level 2 is shown in Figure 5(a) for the subject ship without a bilge keel and Figure 5(b) for the subject ship with a bilge keel. Here, the height from the roll axis is 10.4 meters (80% of the ship breadth), and the distance from the after perpendicular is 39.65 meters (83.92% of the ship length). The vulnerability index decreases as decreasing GM. A smaller GM is required to comply with the criteria for a higher wave height.

Figure 6(a) shows that the subject ship without bilge keel complies with the criteria level 2 when the wave height is smaller than 3.5 meters. However, the ship complies with the criteria for the GM larger than 6 meters, and the wave height is 7.5 meters if the subject ship uses bilge keels. Figure 6(b) shows that the subject ship complies with the criteria when the height from the roll axis is smaller than 55% of the breadth for the subject ship without a bilge keel and larger than 80% of the ship breadth when using bilge keels. Here, the wave height is 4.5 meters. A different result has been found for a ro-ro ferry which does not comply with the criteria. (IMO, 2019b). However, detail parameters induced the different results cannot be identified because the detail of the geometric characteristics of the ship was not available.

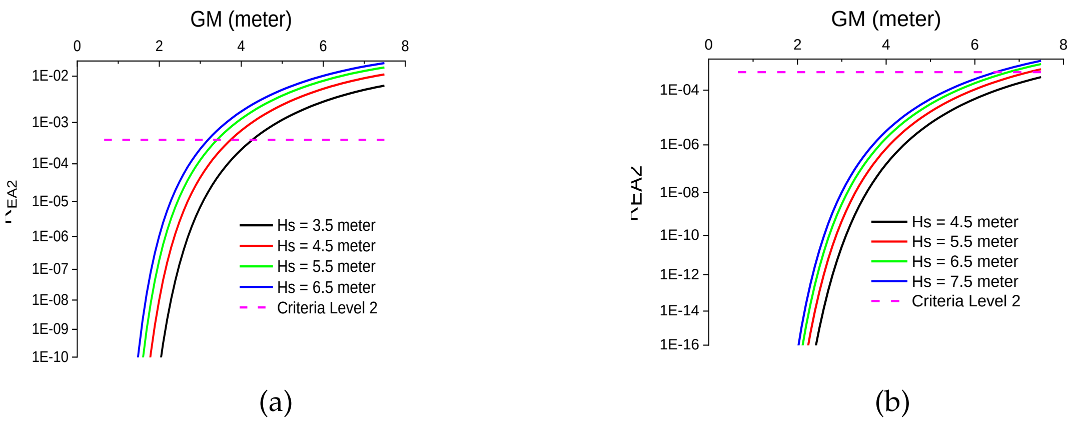
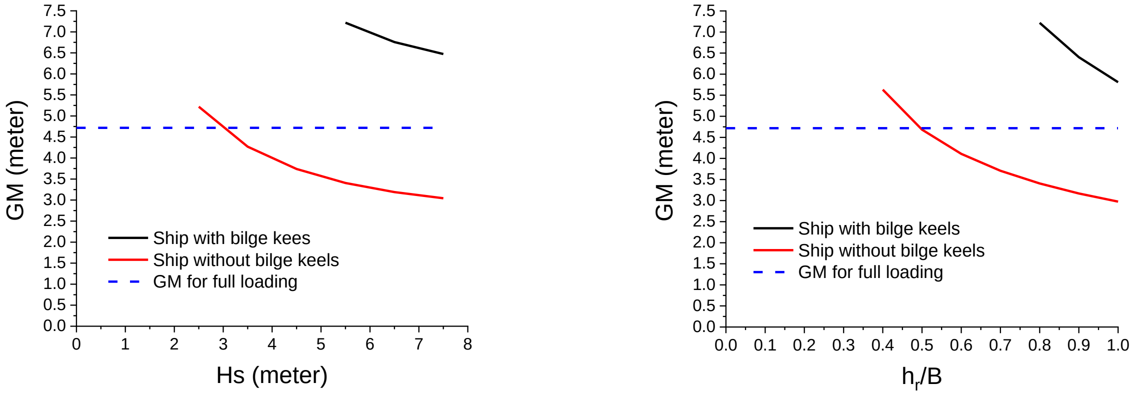


Figure 5 Long-term probability index: (a) Without bilge keels; (b) With bilge keels



(a) (b)

Figure 6 The limitation of GM: (a) Based on the significant wave height; (b) Based on the high of accommodations from the roll axis

Figure 6 shows the significant effect of bilge keel on the limitation of GM. The bilge keel significantly increases the damping coefficients of a ship with a small draught and large vertical center of gravity (Katayama et al., 2018). The significant contribution of bilge keel has also been found for a river-sea ship with a breadth-to-draught ratio of 4.63 and a bilge keel area of 7.1 meters (Rudakovic and Backalov, 2019). The bilge keel area of the present ship is smaller than that of the river-sea ship, but the ratio between the bilge keel area and the ship length multiplied by the ship breadth is larger. Therefore, a more significant effect of bilge keel was found. Those results show that the subject ship does not vulnerable to the excessive acceleration failure mode specified by IMO. A large roll angle can induce a significant lateral acceleration due to the gravitational effect. Overthrowing, however, depends on the postural characteristics of the subject, particularly the ratio between the height of the center of gravity from the deck and half of the subject base's support, as well as a coupled motion of the ship (Freeman et al, 2017; Shigunov et al, 2011).

5. Conclusions

The stability criteria corresponding to the excessive acceleration failure mode of SGISC have been applied to assess the stability of an Indonesian ro-ro ferry with the damping factors determined by the model experiment. Based on the results and discussions, it can be concluded that the non-dimensional logarithmic decrement of roll decay obtained by the formula of IMO is the same as that obtained by the model experiment on the roll angle of 17.45 degrees. The subject ship complies with the criteria for excessive acceleration failure mode even with a significant wave height larger than 7.5 meters. The bilge keel effectively decreases the vulnerability index of the ship. Therefore, it is recommended that the Indonesian ro-ro ferry be designed with bilge keels. The model experiment (roll decay test) can be used as an alternative method to estimate the damping factor for assessing the stability failure corresponding to the excessive acceleration failure mode.

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Author Contributions

Daeng Paroka contribute to conceptualization, design research methodology, simulation software development, formal analysis, writing - original draft preparation, writing - review and editing, supervision, project administration, funding acquisition.

Andi Haris Muhammad contribute to design research methodology, simulation software development, formal analysis, resources, writing - review and editing, and visualisation.

Sabaruddin Rahman contribute to design research methodology, validation, Investigation, data curation, and writing - review and editing.

Conflict of Interest

The authors declare that there is conflict of interest during the preparation and publishing of this work. The funder has not role in the preparation and design of this study; in the collection, analysis, or interpretation of data; in writing of the manuscript, or in the decision to publish the results.

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