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Hydrodynamics Factors Correspond to the Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distributions

Daeng Paroka[1*], Andi Haris Muhammad[2], Sabaruddin Rahman[1]

[1]*Department of Ocean Engineering, Faculty of Engineering, Hasanuddin University, Gowa Campus, Jl. Poros Malino Km. 6 Bontomarannu, Gowa, South Sulawesi, 92171, Indonesia*
[2]*Department of Marine System Engineering, Faculty of Engineering, Hasanuddin University, Gowa Campus, Jl. Poros Malino Km. 6 Bontomarannu, Gowa, South Sulawesi, 92171, Indonesia*

Abstract. The effect of weight distribution on hydrodynamics factors in the weather criterion was investigated. Two types of weight distribution were examined. With the first type of distribution, the weight was concentrated near the centerline of the model. With the second, the weight was positioned farther from the centerline in order to obtain a natural roll period corresponding to that provided by the standard formula in the weather criterion of the International Maritime Organization (IMO). The three-step procedure recommended by the IMO was applied. A roll decay test and a roll test in a regular beam wave were conducted to obtain the natural roll period, the damping factors corresponding to the breadth-to-draught ratio and the bilge keels, and the effective wave slope coefficient. The damping factor corresponding to the breadth-to-draught ratio for the ship with a larger radius of gyration was larger than that for the ship with a smaller radius of gyration. The ship with a smaller radius of gyration had a larger damping factor due to bilge keels compared to the ship with a larger radius of gyration. The effective wave slope coefficient of the ship with the larger radius of gyration was larger than that for the ship with the smaller radius of gyration. The effect of bilge keels on the effective wave slope coefficient for the ship with a radius of gyration equal to that obtained by the weather criterion formula was not significant. The effect of weight distribution on the weather criterion was significant for the ship without bilge keels. A significant effect of bilge keels on the weather criterion occurred for the ship with a weight distribution corresponding to a radius of gyration coefficient closer to that obtained by the formula in the weather criterion.

Keywords: Ro-ro ferry; Roll radius of gyration; Stability; Weather criterion; Weight distribution

1. Introduction

Indonesian ro-ro ferries are used for the inter-island transport of passenger and vehicles, particularly on short-sea and inland river routes. The vehicles are located on the main deck, while the passengers are accommodated in a superstructure above the main deck. The ships are designed with small draughts because the ports in the service areas are generally characterized by shallow water. To satisfy the capacity requirement, the ships are designed with a large breadth. This requirement results in designs with breadth-to-draught ratios of approximately 2.3 to 8.3 (Paroka et al., 2020a). Most of the ships have breadth-to-draught ratios larger than 3.5. The data collected about ro-ro passenger ships

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[*] Corresponding author's email: dparoka@eng.unhas.ac.id, Tel. & Fax.; +62-411-586015

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worldwide also show a breadth-to-draught ratio of approximately 2 to 7.5 (Kristensen, 2016). Indonesian ro-ro ferries have small freeboards to facilitate vehicle loading and unloading at ports. Therefore, the freeboard-to-breadth ratios of most Indonesian ro-ro passenger ferries are smaller than 0.1 (Paroka et al., 2020a). Thus, the heel angle associated with the maximum righting arm is typically smaller than 25° (Paroka, 2018). The vertical center of gravity tends to be larger than the ship's depth because the payload is located above the main deck.

The stability of Indonesian ro-ro ferries is assessed by using the International Code on Intact Stability of the International Maritime Organization (IMO) (IMO, 2008). The weather criterion is one of the criteria applied to ro-ro ships. This criterion was developed based on ships with breadth-to-draught ratios smaller than 3.5, ratios between ship draught and vertical center of gravity ranging from 0.7 to 1.5, and natural roll periods of up to 30 seconds. The values of the variables for calculating the roll angle to windward due to waves may be inappropriate when applied to a ship with geometric characteristics different from those used to develop the criteria (Vassalos et al., 2003; Francescutto, 2007; Sato et al., 2008). For ships with large breadth-to-draught ratios, the associated damping factor was found to be smaller than that obtained with the recommended value of the IMO (Deakin, 2008; Paroka et al., 2020b), and the effective wave slope coefficient obtained with the weather criterion formulae resulted in a larger value than that obtained by model experiments (Fujino et al., 1993; Ishida et al., 2011; Paroka et al., 2020b). Therefore, the IMO has recommended the use of model experiments when the weather criterion is applied to ships with geometric characteristics different from those used to develop the criteria (IMO, 2006). Adjustment values for the effective wave slope coefficient, wave steepness for roll periods of up to 30 seconds, and a damping factor correspond to breadth-to-draught ratio for ships with breadth-to-draught ratios up to 6.5 had been proposed (IMO, 2003; Francescutto, 2015). Recently, an extension of the roll period has been adopted in the International Code on Intact Stability (IMO, 2015), but the damping factors corresponding to the breadth-to-draught ratio and bilge keels as well as the effective wave slope coefficient have not been changed.

The damping factor corresponding to bilge keels in the weather criterion was assumed to depend only on the ratio between the bilge keels area and the product between the length of the waterline and the ship's breadth. However, the damping moment induced by the bilge keels depends on the distance between the bilge keels and the ship's center of gravity in addition to the depth of the bilge keels from the water surface (Ikeda et al., 1978a; Ikeda et al., 1978b).The effect of distance between the bilge keels and the roll axis for a shallow draught ship with a large breadth-to-draught ratio has been verified by Katayama et al. (2018). The increase of the equivalent damping moment was not commensurate with the increasing height of the bilge keels (Jiang et al., 2020). Fesman et al. (2007) found that the use of bilge keels could reduce the roll angle of a ship by about 30%. Therefore, the damping factor due to bilge keels given in the weather criterion results in an overestimated roll angle due to waves when it is applied to a ship with a large breadth-to-draught ratio, as found by Paroka et al. (2020b). The effect of bilge keels on roll motion has been widely investigated, including the effect of dimension and position (Irkal et al., 2014), but the effect on the damping factor in the weather criterion has never been investigated.

Another factor that should be considered when the weather criterion is applied to an Indonesian ro-ro ferry is weight distribution. The loading conditions do not always follow the designed loading plan, in which the heaviest vehicles are meant to be located near the center line. Under certain conditions, depending on the vehicles to be transported, a heavy vehicle can be located near the portside or the starboard. This different payload weight distribution could have significant effects on the natural roll period, as well as on roll damping and the effective wave slope coefficient. However, the adjustment values of these parameters in the weather criterion are independent of weight distribution. The radius of gyration can be calculated by a formula given in the weather criterion. A significant error can be obtained when the formula is applied to a ship with a larger breadth-to-draught ratio and a large metacentric height (GM) (Borisov et al., 2015). The effective wave slope coefficient depends on the wave frequency (IMO, 2013). The damping moment of a roll can decrease due to slower roll motion, which is associated with a larger natural roll period (Grimm et al., 2017). The roll period increases with increasing total inertia of mass, which is calculated based on the weight distribution. The added inertia of a roll increases when the wave frequency increases (Kianejad et al., 2017). This means that the hydrodynamics factors corresponding to the weather criterion can be different due to alterations of the weight distribution. The effect of weight distribution described by variations of the radius of gyration on the roll motion of a ship's midsection with bilge keels has been investigated by Irkal et al. (2017), but the effect on the values of the parameters in the weather criterion has not yet been examined.

This paper discusses the effects of weight distribution on the values of the parameters in the weather criterion applied to an Indonesian ro-ro ferry. This is important because the weight distribution could vary on the basis of the vehicles transported during the operation of the vessels. The effects of weight distribution on the hydrodynamics factors corresponding to the calculation of the roll angle toward windward due to waves can be determined. The effect of bilge keels on the effective wave slope coefficient was also investigated with different weight distributions. The results can be used to develop stability criteria for ro-ro ferries, which have been categorized as non-conventional ships by the IMO, and to extend the tabulated values of damping factors due to breadth-to-draught ratios and bilge keels in the weather criterion. The results can also provide operational guidance for the distribution of vehicles on the main deck of ro-ro ferries.

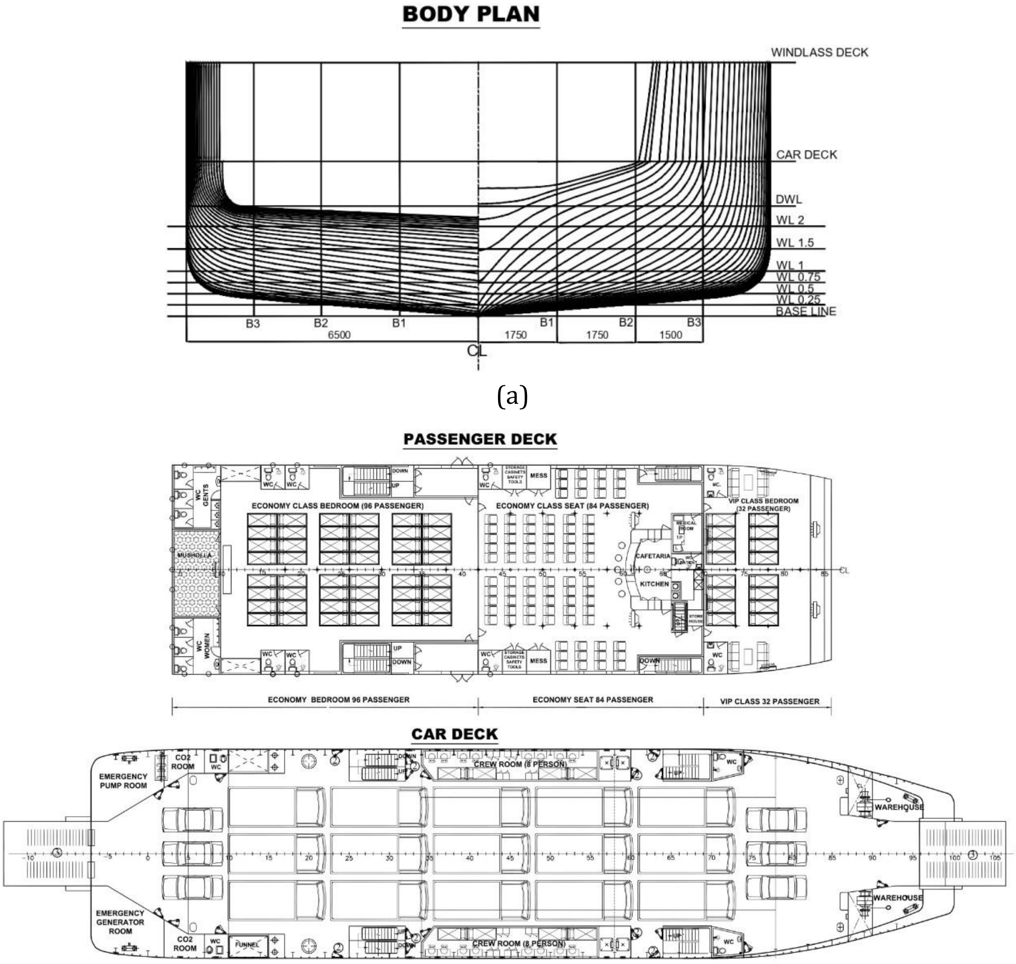
2. Methods

2.1. *Ship Data*

The main dimensions and the body plan of the ship examined in this study are presented in Table 1 and Figure 1a, respectively. The ship had a breadth-to-draught ratio of 5.31. The ratio of the freeboard to the breadth was 0.08, and the ratio of the vertical center of gravity to the ship draught was 1.63. These geometric characteristics were out of the range of the ship data used to develop the weather criterion.

Table 1 Main information of the sample ship

Principal Dimension	Ship(m)	Model(mm)
Overall length (Loa)	54.50	1362.50
Length of the perpendicular (Lbp)	47.25	1181.25
Breadth (B)	13.00	325.00
Draught (T)	2.45	61.25
Depth (D)	3.45	86.25
Vertical position of metacentre (KM)	8.72	218.00
Block coefficient (Cb)	0.62	0.62
Windage area (A_L)	432.93	270581.3
Vertical distance of the centroid of windage area from the water surface (C_L)	4.43	110.75
Lengthof bilge keels	25.50	637.5
Height of bilge keels	0.25	6.25



(a)

(b)

Figure 1 Design information of the ship: (a) Body plan; (b) Deck layout

The loading plan for the vehicle deck had an indication for 12 trucks and 3 small cars in the aft and 3 small cars in the bow, as shown in Figure 1b. The passenger accommodations were located in the superstructure above the vehicle deck.

To investigate the effects of weight distribution, two scenarios were considered. The first scenario considered a weight distribution with a radius of gyration coefficient of 0.36 of a ship's breadth ($k_{xx} = 0.36B$). The second scenario considered a weight distribution with a radius of gyration coefficient close to that obtained with the weather criterion formula (IMO, 2008). For the sample ship, the corresponding radius of gyration coefficient (k_{xx}) was 0.474B, which was larger than the upper limit proposed by Papanikolaou et al. (1997). The vertical center of gravity was kept the same for the two types of weight distribution.

2.2. Experimental Setup

The three-step model experiment procedure recommended by the IMO (IMO, 2006) was used to determine the Bertin's coefficient and the effective wave slope coefficient. Two experiments consisting of a roll decay test and a roll test in regular beam waves were necessary to estimate the values of the parameters of the weather criterion formula. The model scale was 1:40, with model dimensions shown in Table 1. The roll decay test was conducted with an initial heel angle of 25°. The model was released to perform free roll motion and was stopped when the roll amplitude was smaller than 0.5°. The roll angle in the time domain was measured by a dual axis inclinometer connected to a computer (PC_3), as shown in Figure 2, for recording the data. The test was conducted five times for each model configuration, and the damping and Bertin's coefficients were determined as averages of the number of tests.

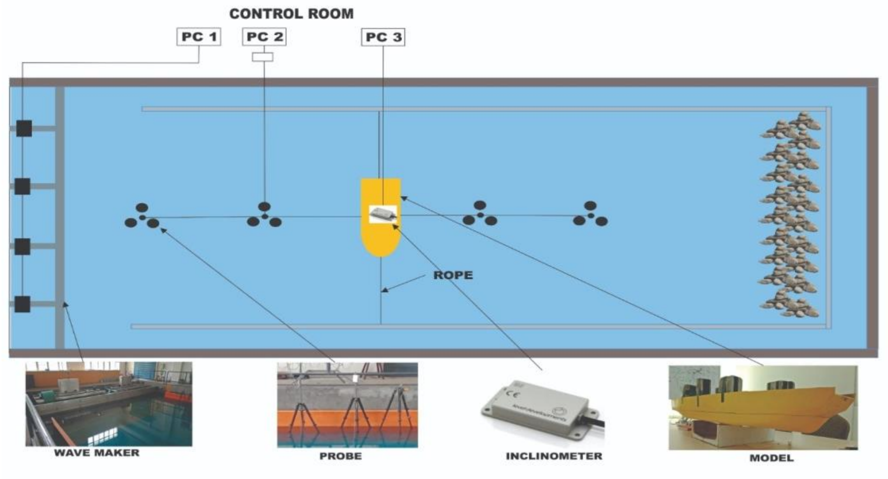


Figure 2 Model setting for roll experiment in a regular beam wave

The roll test in a regular beam wave was performed for wave frequencies of 0.8, 0.9, 1.0, 1.1, and 1.2 of the roll natural frequency and a wave steepness of 0.01, 0.02, 0.03, and 0.04. The model was free to sway, heave, and roll, but it was restricted in terms of surge and yaw by a flexible wire rope installed on the steam and the stern with a level that was the same as the vertical center of gravity, as shown in Figure 2. The roll angle was measured by a dual axis inclinometer located at the midship and connected to a computer (PC_3) for recording the roll angle in the time domain. The wave profile was measured using a wave probe located in the front of and behind the model. The data concerning the wave profile were recorded on the computer (PC_2). The wave maker was run on the computer (PC_1), with the amplitude determined based on the tested frequency and steepness of the wave. The actual wave steepness was calculated based on the recorded wave profile with a calibration factor obtained before running the experiment. The measurement of the wave profile and roll angle began at the same time as the running of the wave maker and lasted for 60 seconds. The roll test was repeated twice for each test condition. The effective wave slope coefficient was determined based on the Bertin's coefficient, the extinction coefficient was obtained by a roll decay test, and the actual wave height and period as measured by the wave probe and the roll amplitude were obtained by the roll test in a regular beam wave. This roll amplitude was determined within the time duration with steady roll motion.

2.3. *Data Analysis*

The roll motion in a regular beam wave was modeled with a single degree of freedom in a nonlinear equation as follows (IMO, 2006):

$$\ddot{\phi} + 2\alpha\dot{\phi} + \beta\dot{\phi}|\dot{\phi}| + {\omega_0}^2(\phi + \gamma_3\phi^3 + \gamma_5\phi^5) = {\omega_0}^2\pi sr\cos(\omega t) \qquad (1)$$

where α ($1/s$) and β ($1/rad$) are the linear and quadratic damping coefficients, respectively. The roll natural frequency was designated by ω_0 (rad/s);γ_3 and γ_5 are the third and fifthorder coefficients of the polynomial equation of the righting arm, respectively;s is the wave steepness, r is the effective wave slope coefficient, and ω (rad/s) is the wave frequency. This equation was used to determine the damping coefficients based on the extinction coefficient obtained by the roll decay test. The order of extinction coefficients depended on the order of the damping moment described in the roll motion equation.

The Bertin's coefficient for a single roll decay test was calculated by using the following equation:

$$N(\phi_m) = \frac{a}{\phi_m} + b \tag{2}$$

where a and b are the extinction coefficients of roll decay, and ϕ_m is the average of two consecutive roll amplitudes of the roll decay test (degree). These coefficients were also used to determine the linear and quadratic damping coefficients in accordance with the International Towing Tank Conference (ITTC) (ITTC, 2011). The effective wave slope coefficient was calculated using the following equation (IMO, 2006):

$$r = \frac{{\phi_r}^2 \cdot N(\phi_r) \cdot g \cdot {T_r}^2}{180 \cdot \pi^2 \cdot H_r} \tag{3}$$

where g is gravity acceleration (9.81 m/s^2). The Bertin's coefficient was determined with Equation 2 with the roll amplitude, ϕ_r, (degree) of the roll test in the regular beam wavesfor the corresponding wave steepness. T_r and H_r are the wave period (second) and the wave height (m), respectively. The roll-back angle in regular waves (degree) was then calculated with the following equation:

$$\phi_{1r} = \sqrt{\frac{90 \cdot \pi \cdot s \cdot r}{N(\phi_{1r})}} \tag{4}$$

where s is the wave steepness given in the weather criterion. This equation was solved iteratively with the initial roll angle of 20°.

The damping factors corresponding to the breadth-to-draught ratio were determined with the weather criterion equation for calculating the roll angle to windward due to waves, as shown in Equation 5. The windward roll angle due to the wave action, ϕ_1, (degree) was assumed to correspond to 70% of the roll amplitude obtained in Equation 4 (IMO, 2006).

$$X_1 = \frac{\phi_1}{109 \cdot X_2 \cdot k \cdot \sqrt{r \cdot s}} \tag{5}$$

where

$$\phi_1 = 0.7 \cdot \phi_{1r} \tag{6}$$

Here, X_2 is the damping factor corresponding to the block coefficient with the value given in the weather criterion; k is the damping factor due to the bilge keels with a value of 1 for a ship without bilge keels. Equation 5 was used to determine the damping factor corresponding to the breadth-to-draught ratio on the basis of the data for the model experiment of a ship without bilge keels. Using the obtained damping factor due to the breadth-to-draught ratio, the damping factor corresponding to the bilge keels was determined as follows:

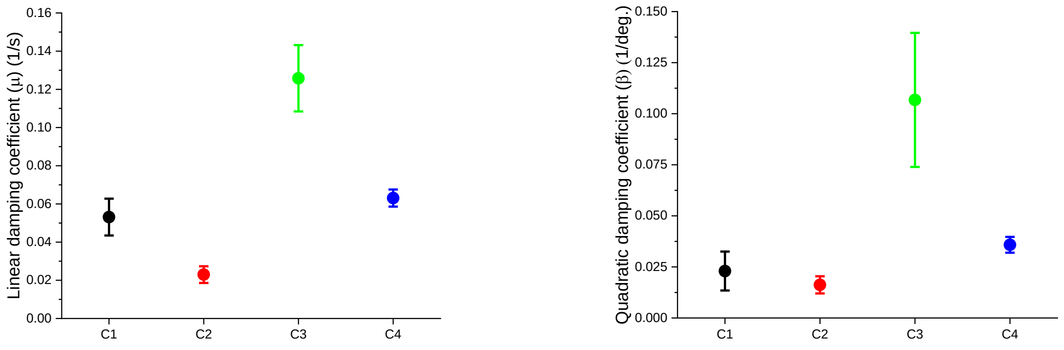
$$k = \frac{\phi_1}{109 \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s}} \tag{7}$$

The roll angle to windward due to waves was based on the results of the regular beam wave test for the ship with the bilge keels. The obtained effective wave slope coefficient and damping factors were used to evaluate the stability of the sample ship on the basis of the weather criterion. A wind pressure of 300 Pa corresponding to a mean wind velocity of 20 m/s was used.

3. Results and Discussion

The linear damping coefficients corresponding to the weight distribution for the ships with and without the bilge keels are shown in Figure 3a. C1 indicates the ship without the bilge keels with a radius of gyration coefficient of 0.36B. C2 signifies the ship without the bilge keels with a radius of gyration coefficient of 0.48B. C3 and C4 correspond to the ship with the bilge keels with radii of gyration coefficients of 0.38B and 0.49B, respectively. The quadratic damping coefficients for the four ship conditions are shown in Figure 3b.

The linear and quadratic damping coefficients decreased because of the increase in the radius of gyration. The linear damping coefficient decreased by approximately 56% for the ship without the bilge keels because of the increase in the radius of gyration; however, the quadratic damping coefficient decreased by approximately 29%. For the ship with the bilge keels, increasing the radius of gyration reduced the linear and quadratic damping coefficients by approximately 50% and 66%, respectively. These results show that for the ship without the bilge keels, the linear damping coefficient was more significantly affected by the weight distribution than by the quadratic damping coefficient. In the case of the ship with the bilge keels, the weight distribution was found to have a similar effect on the linear and quadratic damping coefficients.

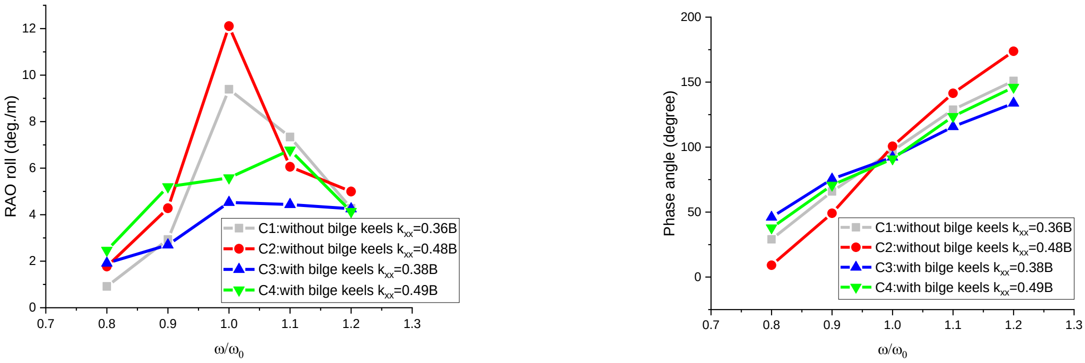


(a) (b)

Figure 3 Roll damping coefficients: (a) Linear; and (b) Quadratic

For the smaller radius of gyration, the linear damping coefficient increased approximately 62% due to the bilge keels. In the case of the larger radius of gyration, the bilge keels increased the linear damping coefficient by approximately 66%. Because of the bilge keels, the quadratic damping coefficient increased by about 73% for the ship with the smaller radius of gyration. For the ship with the larger radius of gyration, the bilge keels increased the quadratic damping coefficient by about 51%. The effect of bilge keels on the quadratic damping coefficient was larger than that on the linear damping coefficient for the ship with a smaller radius of gyration. Conversely, the linear damping coefficient was more affected by the bilge keels for a larger radius of gyration. The angular velocity of roll motion decreased when the roll moment of inertia increased; therefore, the damping moment decreased. Ikeda et al. (1978a) found that the normal force of bilge keels linearly increased as the roll frequency increased. Therefore, the damping coefficient decreased due to the increase of the roll radius of gyration. The effect of bilge keels on the obtained damping coefficients was larger than that obtained by Fesman et al. (2007). The results of numerical simulations have shown that bilge keels can significantly increase the damping moment of a ship (Gu et al., 2015). The damping induced by the bilge keels depends not only on the area of the bilge keels but also on the distance from the vertical center of gravity, especially for ships with large breadth-to-draught ratios (Katayama et al., 2018; Jiang et al., 2020).

The different effects of weight distribution on the damping coefficients for the ships with and without the bilge keels could be induced by the difference in the natural roll periods resulting from the different radii of gyration. The angular velocity of rolling for the condition with a longer roll period was smaller than that for the condition with the shorter roll period. Therefore, the damping coefficients decreased. The natural roll period increased by approximately 7% because of the bilge keels in the condition with a radius of gyration coefficient of 0.36B. A similar value of increasing natural roll period due to bilge keels was presented by Irkal et al. (2014) for a ship with a radius gyration coefficient of 0.346B. For the radius of gyration coefficient of 0.48B, the natural roll period increased by approximately 2% because of the bilge keels. The increase in the natural roll period was attributed to the added moment of inertia induced by the bilge keels during the roll motion (Irkal et al., 2015; Jiang and Yeung, 2017). Here, the effect of the bilge keels on the roll period increased as the radius of gyration decreased. Therefore, the effect of bilge keels on the quadratic damping coefficient for the ship with a smaller radius of gyration was larger than that for the ship with a larger radius of gyration.



(a) (b)

Figure 4 Results of roll tests in a regular beam wave: (a) RAO; and (b) Phase angle

The response amplitude operator (RAO) and the phase angle of the roll obtained by the roll test in a regular beam wave are shown in Figure 4. The RAOs of the ship with a larger radius of gyration were larger than those for the ship with a smaller radius of gyration. These results show that the equivalent damping coefficient of the ship with a smaller radius of gyration was larger than that for the ship with a larger radius of gyration, as shown in Figure 3. The bilge keels significantly affected the roll motion on the resonance frequency for ships with both smaller and larger radii of gyration. The effect of the bilge keels on the RAO of the roll tends to decrease for a wave frequency smaller or larger than the resonance frequency. This means that the contribution of bilge keels to the quadratic damping coefficient is more significant when compared to the contribution of bilge keels to the linear damping coefficient. The effect of bilge keelson the damping moment was significantly affected by the roll amplitude and the roll frequency. The phase angle of the roll tends to decrease due to the decrease of the damping coefficient for a wave frequency smaller than the roll natural frequency. For a wave frequency larger than the roll natural frequency, the phase angle increases when the damping coefficient increases, as shown in Figure 4b.

The effective wave slope coefficient obtained under the test conditions is shown in Figure 5. This coefficient corresponded to the roll natural frequency of the ship. The effective wave slope coefficient tended to increase as the wave steepness increased, mainly for a larger radius of gyration. These results indicate that the nonlinear effect plays an important role mainly for a short wavelength region. Similar results have been found for a ship with a breadth-to-draught ratio of 5.83 (Sato et al., 2008).The wave height may also have an effect on the effective wave slope coefficient, as the coefficient obtained for an approximately constant wavelength corresponds to a roll natural frequency for each test condition. For a ship with a low freeboard, Umeda et al. (2019) found that the effective wave slope coefficient decreased when the wave steepness increased due to trapped water on the deck, especially at a large wave steepness. In the present study, there was no occurrence of trapped water on deck. For the ship with the radius of gyration coefficient of 0.48B or larger, the bilge keels had no significant effect on the effective wave slope coefficient. This is because the roll natural frequency of the ship did not significantly increase due to bilge keels in the case of a radius of gyration of 0.48B.

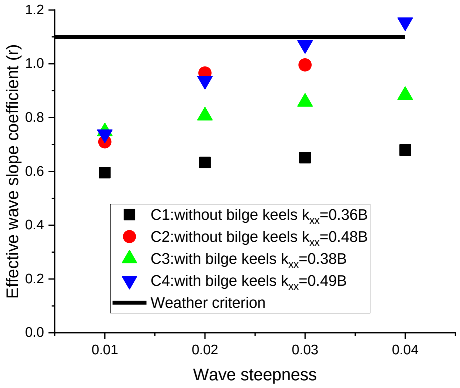


Figure 5 Effective wave slope coefficient

Regarding the smaller radius of gyration, the effective wave slope coefficient of the ship with bilge keels was larger than that of the ship without the bilge keels. In this case, the increase of the roll natural period was larger compared to that for the radius gyration of 0.48B. Therefore, the effective wave slope coefficient was significantly different. The effective wave slope coefficients, which were obtained with the weather criterion formula, were smaller than 1.099, except for the ship with bilge keels and a larger radius of gyration, for which the wave steepness was 0.04. The effective wave slope coefficient obtained with the weather criterion formula was similar to that obtained for the case with the same natural roll period as that obtained with the formula in the weather criterion for a wave steepness of 0.03.This is crucial for Indonesian ro-ro ferries because the weight distribution on the vehicle deck is based on the type of vehicles to be transported. Therefore, the effect of weight distribution on the parameter values of the weather criterion should be considered for Indonesian ro-ro ferries.

The damping factors corresponding to the breadth-to-draught ratio and the bilge keels of the subject ship are shown in Table 2. The damping factor corresponding to the breadth-to-draught ratio of the subject ship with a radius of gyration coefficient that was approximately the same as those obtained by the weather criterion formulae was 0.674.

Table 2 The damping factors obtained by model experiments and the weather criterion

Scenario	k_{xx}	X_1		k	
		Present results	Weather criterion	Present results	Weather criterion
C1	0.36 B	0.470	0.80	1.00	1.00
C2	0.48 B	0.674	0.80	1.00	1.00
C3	0.38 B	0.470	0.80	0.73	089
C4	0.49 B	0.674	0.80	0.61	0.89

This damping factor was smaller than that in the weather criterion for ships with breadth-to-draught ratios larger than 3.5 (X_1 =0.8). For a smaller radius of gyration coefficient, the damping factor due to the breadth-to-draught ratio was 0.47. A damping factor smaller than that recommended by the IMO was also found by Deakin (2008). Therefore, the damping factor corresponding to the breadth–to-draught ratio in the weather criterion should be extended to cover ships with breadth-to-draught ratios larger than 3.5.

The obtained damping factor due to the bilge keels was smaller than that recommended in the weather criterion, as shown in Table 2. The damping factor due to the bilge keels for the radius of gyration coefficient that was the same as that obtained with the weather criterion formulae was 0.61. The damping factor for the smaller radius of gyration coefficient was 0.73. These damping factors were smaller than that based on the weather criterion of 0.89 corresponding to the ratio between the bilge keels area and the product between the length of the waterline and the breadth of the ship of 1.923. The damping factor corresponding to the bilge keels decreased by approximately 16% because of the increase in the radius of gyration coefficient from 0.38B to 0.49B. When the radius of gyration increased, the natural roll period also increased, and the damping coefficient decreased. Therefore, for the ship with the larger radius of gyration coefficient, the total damping factor resulting from the breadth-to-draught ratio and the bilge keels was larger than that with the smaller radius of gyration coefficient. The increase in the total damping factor resulting from the increase in the radius of gyration was approximately 17%. This is because of the smaller damping factor corresponding to the breadth-to-draught ratio for the ship with a smaller radius of gyration compared to the ship with a larger radius of gyration.

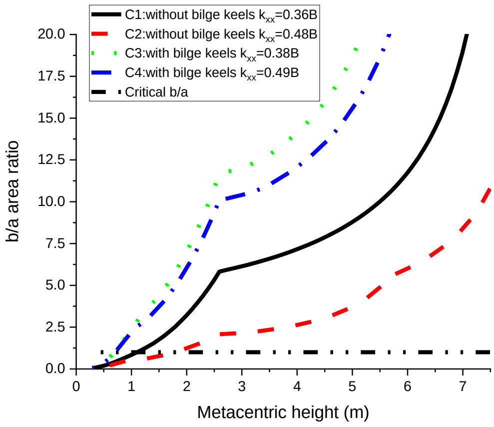


Figure 6 The b/a area ratio of the weather criterion

The weather criterion was calculated by using the obtained damping factors due to the breadth-to-draught ratio, the damping factor due to the bilge keels, and the effective wave slope coefficient. The b/a area ratio for the vertical center of gravity of 1.227 m to 8.427 m corresponded to a metacentric height of 0.293 m to 7.493 m, as shown in Figure 6. For the ship without the bilge keels, the weight distribution had a significant effect on the b/a area ratio; however, the effect was small for the ship with the bilge keels. The wave steepness was not different because the natural roll period remained below 6 seconds for all weight distributions. The damping coefficients tended to decrease if the radius of gyration coefficient increased for the ships both with and without the bilge keels. The effective wave slope coefficient of the ship with the smaller radius of gyration was significantly affected by the bilge keels compared to the ship with the larger radius of gyration. The critical metacentric height was 1.193 m for the C1 condition and 1.793 m for the C2 condition. The obtained minimum metacentric height was 0.693 m for the C3 condition and 0.793 m for the C4 condition. This means that the critical metacentric height of the Indonesian ro-ro ferry could alternate between 0.793 m and 1.793 m due to variations in weight distribution.

In the operational condition with the metacentric height of 4 m, the b/a area ratio of 7.15 for the C1 condition and 2.62 for the C2 condition decreased by approximately 63% because of the increase in the radius of gyration. The b/a area ratio decreased by 15% when the ship used the bilge keels. The effect of the bilge keels on the weather criterion was more significant for the larger radius of gyration. The b/a area ratio increased by approximately 78% because of the bilge keels for the subject ship with the radius of gyration of the C2 condition to be the C4 condition. The increase was approximately 49% for the radius of gyration of the C1 condition to be the C3 condition.

4. Conclusions

The damping factors corresponding to the weather criterion and the effective wave slope coefficients of an Indonesian ro-ro ferry with and without bilge keels and with different weight distributions were determined in model experiments. The value for the damping factor related to the breadth-to-draught ratio for the ship with a radius of gyration that was approximately the same as that calculated by the weather criterion formula (0.48B) was larger than that for the ship with a radius of gyration of approximately 0.36B. The damping factor corresponding to the bilge keels for the ship with a radius of gyration of 0.49B was smaller compared to that for the ship with a radius of gyration of 0.38B. The effective wave slope coefficient of the ship with a radius of gyration of 0.48B was larger than that of the ship with a radius of gyration of 0.36B. The formula used to calculate the effective wave slope coefficient can be applied to an Indonesian ro-ro ferry if the radius of gyration is equal to that calculated by the formula of the weather criterion. The effective wave slope coefficient for the ship with a radius of gyration approximately equal to that calculated with the weather criterion formula was not significantly affected by the bilge keels. The effect of weight distribution on the b/a area ratio of the weather criterionwas more significant for the ship without bilge keels compared to the ship with bilge keels. The bilge keels give a more significant contribution to the b/a area ratio in the case of a weight distribution with a radius of gyration coefficient close to that obtained by the formula of the weather criterion. Therefore, it is recommended to use a model experiment as an alternative method to determine the values of parameters in the weather criterion when that criterion is applied to ships with a breadth-to-draught ratio larger than 3.50 and with a ratio between the vertical center of gravity and a ship draught larger than 1.50.

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