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[IJTech] Manuscript Submission Confirmation for ME-4246

Inbox

IJTech <noreply@ijtech.eng.ui.ac.id>

Wed, Aug 5, 2020, 1:40 PM

to me

Manuscript Submission Confirmation

Dear Dr. Daeng Paroka,

Your manuscript entitled **"Hydrodynamics Factors Correspond to Weather Criterion Applied to Ro-Ro Ferry with Different Weight Distribution"** has been successfully submitted to International Journal of Technology (IJTech) Online System.
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[IJTech] Revise initial screening manuscript #ME-4246

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to me, andi_haris, sabaruddin-r

Screening result : Revise

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conclusion should based on the result.
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IJTech <noreply@ijtech.eng.ui.ac.id>

Tue, Aug 25, 2020, 10:15 PM

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Tue, Oct 20, 2020, 1:00 AM

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Revision Reminder

Ms ID **#ME-4246**
Title : Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution
Author(s) : Daeng Paroka, Andi Haris Muhammad, Sabaruddin Rahman
Dear Dr. Daeng Paroka:

This is a polite reminder that we recently requested a revision of your manuscript, which is now due on **[27 Oct 2020]**. If we do not receive your revision within that time, we will assume that you are not sending a revision and this constitutes your manuscript being inactivated.
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Revision Reminder

Ms ID **#R1-ME-4246**
Title : Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution
Author(s) : Daeng Paroka, Andi Haris Muhammad, Sabaruddin Rahman
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Revision Reminder

Ms ID **#R1-ME-4246**
Title : Hydrodynamics Factors

Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution
Author(s) : Daeng Paroka, Andi Haris Muhammad, Sabaruddin Rahman
Dear Dr. Daeng Paroka:

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[IJTech] Manuscript Submission Notification for R1-ME-4246

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IJTech <noreply@ijtech.eng.ui.ac.id> Tue, Nov 10, 2020, 11:54 AM

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[IJTech] Revision reminder for manuscript #R1-ME-4246

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IJTech <noreply@ijtech.eng.ui.ac.id> Tue, Dec 1, 2020, 1:00 AM

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Ms ID **#R1-ME-4246**
Title : Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution
Author(s) : Daeng Paroka, Andi Haris Muhammad, Sabaruddin Rahman
Dear Dr. Daeng Paroka:

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Mon, Dec 7, 2020, 9:56 AM

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https://ijtech.eng.ui.ac.id/

IJTech] Editor Decision

Inbox

IJTech <noreply@ijtech.eng.ui.ac.id>

Mon, Jan 4, 3:59 PM

to me, andi_haris, sabaruddin-r

Editor Decision on #R2-ME-4246 : Accepted

Ms ID **#R2-ME-4246**
Title : Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution
Author(s) : Daeng Paroka, Andi Haris Muhammad, Sabaruddin Rahman

Dear **Dr. Daeng Paroka** ,
Greetings from Depok,

The editorial board is delighted to inform you that your paper entitled "Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution" has been accepted to be published on IJTech. **Congratulation!**
In order to ensure the readability and the quality of the journal, Starting from 1st of January 2020, all accepted articles to publish will be subjected to

article processing charge (APC) of US$ 550 for Regular Publication or US$ 650 for Special Edition Publication, as announced in IJTech's website. This fee covers the review process, line editing, layouting, DOI deposit, printing, and shipping cost.
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Warmest regards,

Dr. Mohammed Ali Berawi
maberawi@eng.ui.ac.id
Editor in Chief
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[IJTech-ME-4246] Result of Line-editing of the Paper

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IJTech <ijtech@eng.ui.ac.id>

Fri, Jan 15, 11:06 AM

to me, andi_haris, sabaruddin-r

Dear Dr. Daeng Paroka,

We have conducted line editing for your paper as part of the publication process in IJTech. Enclosed, please find the comments from the line editor indicated by the character in color besides black.
We would like to ask you to complete the following:

1. **Please make necessary revise the paper accordingly to the line editor comments.**
2. **Please make sure the detailed information for the name of the author(s), and affiliation of each author(s). Please refer to Guideline for Author to write the affiliation section (https://ijtech.eng.ui.ac.id/about/3/online-submission**

After the revision complete, please send it back to ijtech@eng.ui.ac.id or reply to this email, no later than **January 17, 2021**
We will proceed to the next step (Layouting, Final proof & Copyright) of the revised paper before printing.

We are looking forward to receiving your revised paper soon.

--
Kind regards,
Secretariat IJTech
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[IJTech-ME-4246] Final Proof reading & Copyright form

Inbox

IJTech <ijtech@eng.ui.ac.id>

Tue, Jan 19, 11:46 AM

to me, andi_haris, sabaruddin-r

Dear Dr. Daeng Paroka,

The editorial boards delighted to inform you that your paper has been accepted to be published in IJTech next Volume 12 issue 1, January 2021.

Congratulations!

We have carried out necessary layouting and editing of your manuscript. Prior to publication we need your final proof and copyright of the paper. Here is note from editor:

1. **Please provide the corresponding author's telephone and fax number (if any)**
2. **It is suggested to include at least 3 relevant IJTech articles as references**

Enclosed please find the copyright form and the paper for a final check and please confirm that the article ready for printing.
Any confirmation of the final check should be submitted on **January 20, 2021.**
Copyright form can be printed, signed, scanned and
send by email to ijtech@eng.ui.ac.id.

On behalf of editorial boards, we want to express you and your collaborators our deep appreciation for your contribution to IJTech.

We look forward to receiving the copyright form and proofs at your earliest convenience.

Yours sincerely,

Dr. Mohammed Ali Berawi
maberawi@eng.ui.ac.id
Editor in Chief
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[IJTech] Your manuscript is published at Volume 12 Issue 1, Jan 2021

Inbox

IJTech <noreply@ijtech.eng.ui.ac.id> Mon, Jan 25, 7:20 PM

to me

Journal Publishing

Dear Dr. Daeng Paroka,

Greetings from Depok!

On behalf of the Editorial Board, I am pleased to inform you that your article entitled **Hydrodynamics Factors Correspond to the Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distributions** has been published online in *Volume 12 Issue 1, Jan 2021*. You can check the online version at: https://ijtech.eng.ui.ac.id/issue/69 The articles are available to be accessed and downloaded free of charge. The hardcopy version is being printed and one copy will be delivered to the corresponding author.

Thank you for your contribution to IJTech and we look forward to a good collaboration in the next future.

Yours sincerely,

Dr. Mohammed Ali Berawi
maberawi@eng.ui.ac.id
Editor in Chief
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artikel_paroka_submission_revised_round_1

International Journal of Technology v(i)pp-pp (YYYY)
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Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution

Put authors name here[1*], Put author name here[1], Put author name here[1], Put author name here[2], Put authors name here[2]

[1]*Put author's affiliation here, complete with address, postal code, and country*
[2]*Put author's affiliation here, complete with address, postal code, and country*

Abstract. The effect of weight distribution to 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 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 International Maritime Organization (IMO). The three-step procedure recommended by the IMO was applied. Roll decay test and roll test in regular beam wave were conducted to obtain the natural roll period, the damping factors correspond to the breadth-to-draught ratio and the bilge keels, and the effective wave slope coefficient. The damping factor corresponds to the breadth-to-draught ratio for ship with larger radius of gyration is larger than that for the ship with smaller radius of gyration. The ship with smaller radius of gyration has a larger damping factor due to bilge keels compared to the ship with 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 effective wave slope coefficient for the ship with radius of gyration equal to that obtained by the weather criterion formula was not significant. Effect of weight distribution on the weather criterion is significant for ship without bilge keels. A significant effect of bilge keels on the weather criterion occurs to the ship with weight distribution corresponds to radius of gyration coefficient closed to that obtained by the formula in the weather criterion.

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

1. Introduction

The Indonesian ro-ro ferries are used in the inter-island particularly on short-sea routes, inland, and river transportation of passengers and vehicles. The vehicles are located on the main deck and 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. These requirements result 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 collected data of ro-ro passenger ships around the world also show the breadth-to-draught ratio of approximately 2 to 7.5 (Kristensen, 2016).

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doi: 10.14716/ijtech.v0i0.0000

The 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 centre of gravity tends to be larger than the ship depth because the payload is located above the main deck.

The stability of Indonesian ro-ro ferries are assesed by using the International Code on Intact Stability of International Maritime Organization (IMO) (IMO, 2008). The weather criterion is one of the criteria applied to ro-ro ships. This criteria was developed based on ships with breadth-to-draught ratios smaller than 3.5, ratio between the vertical center of gravity and the ship draught ranges from 0.7 to 1.5 and the natural roll periods of up to 30 seconds. The values of the variables for calculating the roll angle to windward due to wave could be unappropriate when it is 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 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). The adjustment values for the effective wave slope coefficient, wave steepness for roll periods up to 30 seconds, and damping factor due to breadth-to-draught ratio for ships with breadth-to-draught ratios up to 6.5 had been proposed (IMO, 2003; Francescutto, 2015). Recently, the extension of the roll period has been adopted in the International Code on Intact Stability (IMO, 2008) but the damping factors correspond to breadth-to-draught ratio and bilge keels as well as the effective wave slope coefficient have not been changed.

The damping factor corresponds to bilge keels in the weather criterion was assumed to be depend only on the ratio between the bilge keels area and the product between the length of waterline and the ship breadth. However, the damping moment induced by the bilge keels depend on the distance between the bilge keels and the ship centre of gravity and 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 large breadth-to-draught ratio has been verified by Katayama, et al (2018). The increasing of equivalent damping moment was not linear with the increasing of height of bilge keels (Jiang, et al, 2020). Fesman, et al (2007) found that the using of bilge keels could reduce the roll angle of a ship about 30%. Therefore, the damping factor due to bilge keels given in the weather criterion results in an overestimate roll angle due to wave 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 investigate including the effect of dimension and position of bilge keels (Irkal, et al, 2014) but the effect on damping factor in the weather criterion has never been investigated.

The others factors should be considered when the weather criterion 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 to be located near the centre 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 weight distribution of payload could have significant effects on the roll natural period, the roll damping, and the effective wave slope coefficient. However, the adjusting values of these parameters in the weather criterion are independent of weight distribution. The radius of gyration was calculated by formula given in the weather criterion. A significant error can be obtained when the formula was applied to a ship with larger breadth-to-draught ratio and large metacentric height (GM) (Borisov, et al, 2015). The effective wave slope coefficient depends on the wave frequency (IMO, 2013). The damping moment of roll can decrease due to slower roll motion associate with a larger roll natural period (Grimm, et al., 2017). The roll period increases with increasing of the total inertia of mass which is calculated based on the weight distribution. The added inertia of roll increases when the wave frequency increases (Kianejad, et al, 2017). This means that the hydrodynamics factors correspond to the weather criterion can be different due to alteration of the weight distribution. The effect weight disribution described by variation of radius of gyration on roll motion of a ship midsection with bilge keels has been investigated by Irkal, et al (2017) but the effect on the values of parameters in the weather criterion have never been investigated.

This paper discusses the effects of weight distribution on the parameters values of weather criterion applied to an Indonesian ro-ro ferry. This is important because the weight distribution could vary on the basis of the vehicles that are transported during the operation of the vessels. The effects of the weight distribution on the hydrodynamics factors correspond to the calculation of roll angle toward windward due to the wave can be determined. The effect of bilge keels to the effective wave slope coefficient is also investigated with different weight distribution. The results can be used to develop stability criteria of ro-ro ferry which has been categorized as non-convention ships by the IMO and to extent the tabulated values of damping factors due to breadth-to-draught ratio and the 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.

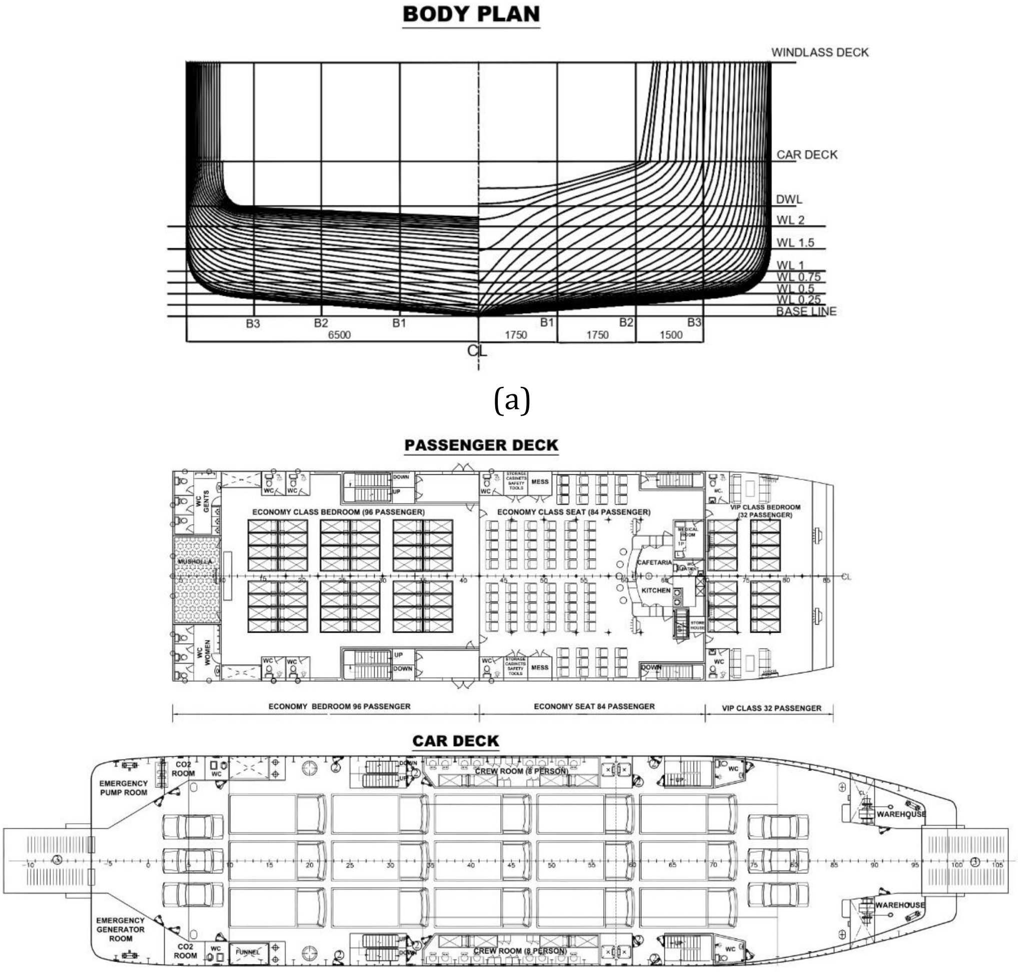
2. Methods

2.1. Ship Data

The main dimensions and the body plan of subject ship 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 centre of gravity to the ship draught was 1.63. Those geometric characteristics were out of the range of ship data used to develop the weather criterion.

Table 1 Main information of the sample ship

Principles 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 metacenter (KM)	8.72	218.00
Block coefficient (Cb)	0.62	0.62
Windage area (A_L)	432.93	0.271
Vertical distance of the centroid of windage area from the water surface (C_L)	4.43	0.111



(a)

(b)

Figure 1 Desain information of the ship: (a) Body plan; and (b) Decks 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 accomodation was located in superstrucutre above the vehicle deck.

To investigate the effects of weight distribution, two scenarios were considered. The first scenario considered weight distribution with radius of gyration coefficient of 0.36 of ship breadth (0.36B). The second scenario was the weight distribution with 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 was 0.474B, which was larger than the upper limit proposed by Papanikolaou et al. (1997). The vertical centre of gravity was kept the same for the two types of weight distribution.

2.2. Experimental Setup

The three-step procedure of model experiment recommended by IMO (IMO, 2006) was used to determined the Bertin's coefficient and the effective wave slope coefficient. Two experiments consist of roll decay test and roll test in regular beam waves are necessary to estimate the values of parameters of weather criterion formula. The model scale was 1 : 40 with model dimensions shown in Table 1. The roll decay test was conducted with the initial heel angle of 25°. The model is released to perform free roll motion and it was stopped when the roll amplitude was smaller than 0.5°. The roll angle in time domain is 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 configurations and the damping and the Bertin's coefficients are determined as average of the number of test.

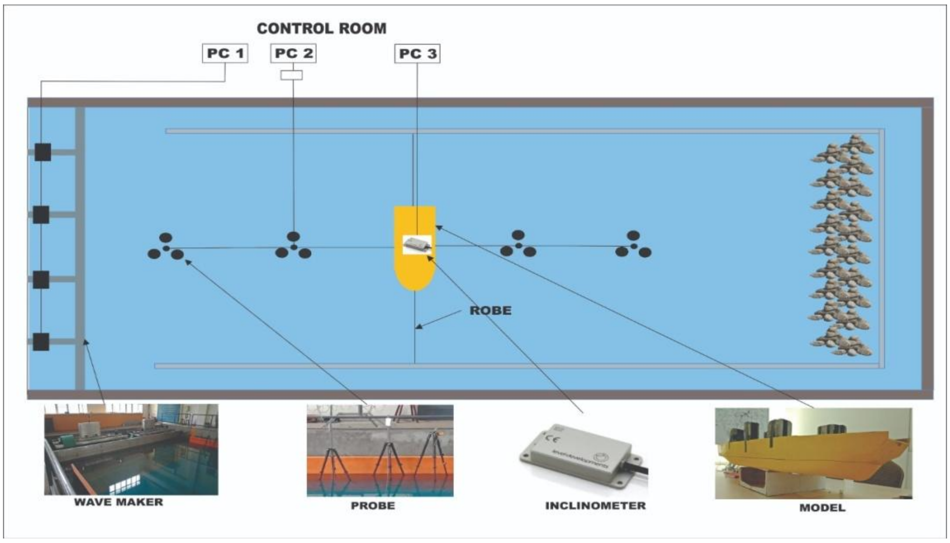


Figure 2 Model setting for experiment of roll in regular beam wave

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

2.3. Data Analysis

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

$$N(\phi_m) = \frac{a}{\phi_m} + b \tag{1}$$

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

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

where g is gravity acceleration (9.81 m/s^2). The Bertin's coefficient was determined with equation (1) with the roll amplitude, ϕ_r, (degree) of the roll test in the regular beam waves for the corresponding wave steepness. T_r and H_r were 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:

$$\phi_{1r} = \sqrt{\frac{90 \cdot \pi \cdot s \cdot r}{N(\phi_{1r})}} \tag{3}$$

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 wave, as shown in equation (4). 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 (3) (IMO, 2006).

$$X_1 = \frac{\phi_1}{109 \cdot X_2 \cdot k \cdot \sqrt{r \cdot s}} \tag{4}$$

where

$$\phi_1 = 0.7 \cdot \phi_{1r} \tag{5}$$

Here, $X_2$was 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 value of 1 for ship without bilge keels. Equation (4) 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 ship without the bilge keels. Using the obtained damping factor due to the breadth-to-draught ratio, the damping factor corresponds to the bilge keels was determined as follow:

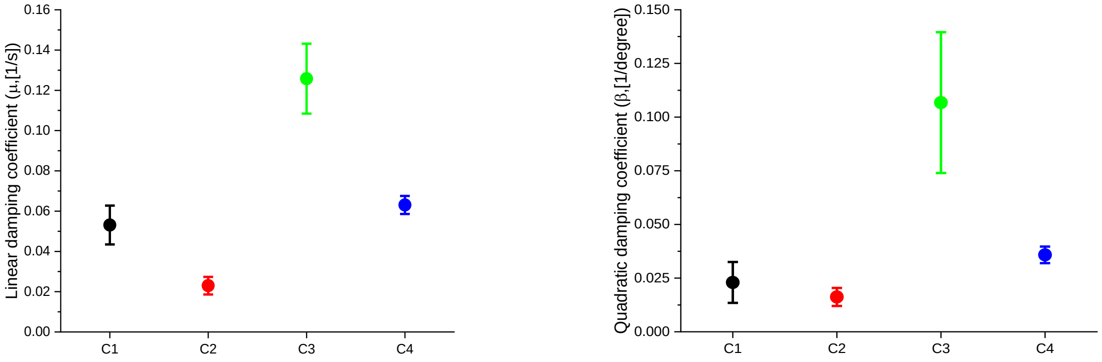
$$k = \frac{\phi_1}{109 \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s}} \tag{6}$$

The roll angle to windward due to wave was based on the results of the test in regular beam wave 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 weather criterion. A wind pressure of 300 Pa correspond to mean wind velocity of 20 m/s was used.

3. Results and Discussion

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

The linear and the 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 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 the quadratic damping coefficients.

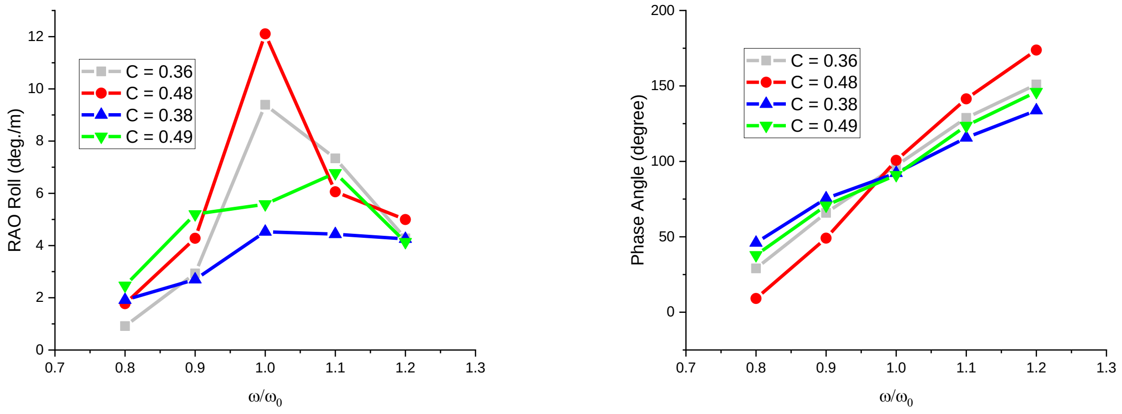


(a) (b)

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 approximately 66%. Because of the bilge keels, the quadratic damping coefficient increased about 73% for the ship with smaller radius of gyration. For the ship with a larger radius of gyration, the bilge keels increased the quadratic damping coefficient about 51%. The effect of bilge keels on the quadratic damping coefficient is larger than that on linear damping coefficient for the ship with smaller radius of gyration. Oppositely, the linear damping cofficient was more affected by the bilge keels for a larger radius of gyration. The angular velocity of roll motion decreases when the roll moment of inertia increase, therefore the damping moment decrease. Ikeda, et al (1978a) found that the normal force of bilge keels linearly increase as the roll frequency increase. Therefore the damping coefficient decrease due to increase of roll radius gyration. The effect of bilge keels on the obtained damping coefficients is larger than that obtained by Fesman, et al (2007). Results of numerical simulation 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 on not only the area of the bilge keels but also the distance from the vertical centre of gravity, especially for ships with large breadth-to-draught ratios (Katayama et al., 2018; Jiang, et al, 2020).

The different effects of the weight distribution on the damping coefficients for the ship 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 roll natural period increased by approximately 7% because of the bilge keels in the condition with a radius of gyration coefficient of 0.36B. A similiar value of increasing the natural roll period due to bilge keels has been 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 roll natural 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 increase as the radius of gyration decreased. Therefore the effect of bilge keels on quadratic damping coefficient for the ship with 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 regular beam wave: (a) RAO; and (b) Phase angle

The response amplitude operator (RAO) and phase angle of roll obtained by roll test in regular beam wave are shown in Figure 4a. The RAOs of ship with larger radius of gyration were larger than those for ship with smaller radius of gyration. These results show that the equivalent damping coefficient of ship with smaller radius of gyration was larger than that for ship with larger radius of gyration as shown in Figure 3. The bilge keels was significantly affect the roll motion on the resonance frequency for both the ship with smaller and larger radii of gyration. The bilge keels effect on RAO of roll tends to decrease for the wave frequency smaller or larger than the resonance frequency. This means that contibution of bilge keels on quadratic damping coefficient was more significant compared to the bilge keels contribution on linear damping coefficient. The bilge keels effect on damping moment significantly affected by the roll amplitude and the roll frequency. The phase angle of roll tends to decrease due to decrease of damping coefficient for wave frequency smaller than the roll natural frequency. For wave frequency larger than the roll natural frequency, the phase angle increase 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. These coefficients 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 indicated that the nonlinear effect play an important role mainly for short wave-negth region. A similiar results have been found for a ship with breadth-to-draught ratio of 5.83 (Sato, et al, 2008). The wave height may also have effect on the effective wave slope coefficient as the coefficient obtained for approximately constant wave length corresponding to 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 deck, especially at 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 case of radius of gyration of 0.48B.

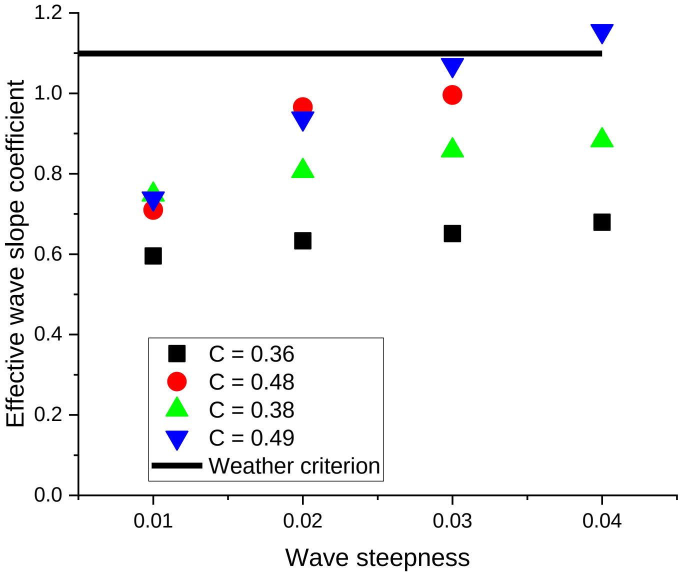


Figure 5 Effective wave slope coefficient

Regarding the smaller radius of gyration, the effective wave slope coefficient of the ship with bilge keels was larger than that without the bilge keels. In this case, the increasing of 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 obtained effective wave slope coefficients were smaller than 1.099, which was obtained with the weather criterion formula except for the ship with bilge keels and a larger radius of gyration when the wave steepness is 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 wave steepness of 0.03. This is crucial for the Indonesian ro-ro ferries because the weight distribution on the vehicle deck is based on the type of vehicles to be transported. Therefore, effect of weight distribution on the parameters values of weather criterion should be considered for the Indonesian ro-ro ferries.

The damping factors correspond to breadth-to-draught ratio and bilge keels of the subject ship were shown in Table 2. The damping factor corresponding to the breadth-to-draught ratio of the subject ship with the radius of gyration coefficient approximately the same as those obtained by the weather criterion formulae was 0.674. 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 breadth-to-draught ratio was 0.47. A smaller damping factor 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.

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

Scenario	k_{44}	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	0.98
C4	0.49 B	0.674	0.80	0.61	0.98

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 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 0.98. 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 factors 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 smaller damping factor correspond to breadth-to-draught ratio for ship with smaller radius of gyration compared to the ship with a larger radius of gyration.

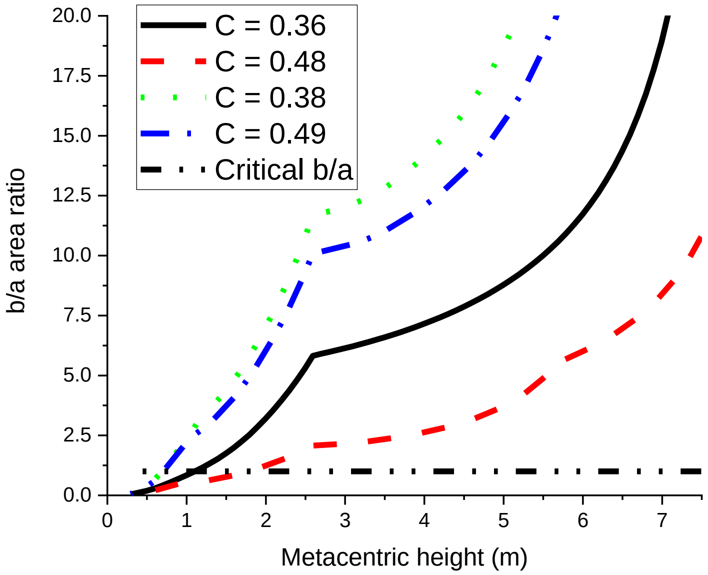


Figure 6 The b/a area ratio of weather criterion

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 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 is 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 is 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 ship both without and with 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 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 alterate between 0.793 m and 1.793 m.

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 C2 condition to be C4 condition. The increase was approximately 49% for radius of gyration of C1 condition to be C3 condition.

4. Conclusions

The damping factors correspond to the weather criterion and the effective wave slope coefficients of an Indonsian ro-ro ferry without and with 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 radius of gyration approximately the same as that calculated by weather criterion formula (0.48B) was larger than that for the ship with radius of gyration of approximately 0.36B. The damping factor corresponds to the bilge keels for the ship with radius of gyration of 0.49B was smaller compared to that for the ship with radius of gyration of 0.38B. The effective wave slope coefficient of the ship with the radius of gyration of 0.48B was larger than that of the ship with the radius of gyration of 0.36B. The formula to calculate the effective wave slope coefficient can be applied to an Indonesian ro-ro ferry if the radius of gyration equal to that calculated by the formula of 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 did not significantly affected by the bilge keels. Effect of weight distribution on the b/a area ratio of weather criterion is more significant for the ship without bilge keels compared to the ship with bilge keels. The bilge keels gives more significant contribution to the b/a area ratio in case of weight distribution with radius of gyration coefficient closed to that obtained by the formula of weather criterion. Therefore it is recommended to used model experiment as an alternative method to determined the values of parameters in the weather criterion when that criteria is applied to ships with breadth-to-draught ratio larger than 3.50 and the ratio between vertical centre of gravity and ship draught larger than 1.50.

Acknowledgements

This paper is part of the research supported by the Directorate General of Higher Education of Indonesia and Hasanuddin University: Grant No.1516/UN4.22/PT.01.03/

2020. The authors express their sincere gratitude to the institutions for their support. The author expresses appreciation to Ardedi Yusuf for his assitance during the experiments.

References

Borisov, R., Luzyanin, A., Kuteynikov, M., Samoylov, V., 2015. An Approach to Assess the Excessive Acceleration Based on Defining Roll Amplitude by Weather Criterion Formula with Modified Applicability Range. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 601 – 612

Deakin, B., 2008. Evaluation of the Roll Prediction Method in the Weather Criterion. *International Journal of Maritime Engineering*, Volume 150(2), pp. 56 – 67

Fesman, E., Bayraktar, D., Taylan, M., 2007. Influence of Damping on the Roll Motion of Ships. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 127 – 134

Francescutto, A., 2007. The Intact Ship Stability Code: Present Status and Future Development. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 199 – 208

Francescutto, A., 2015. Intact Stability Criteria of Ships – Past, Present and Future. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 1199 – 1209

Fujino, M., Fuji, I., Hamamoto, M., Ikeda, Y., Ishida, S., Morita, T., Tanai, K., Umeda, N., 1993. Estimation of Roll Damping Coefficients and Effective Wave Slope Coefficients for Small Passenger Crafts. *In:* Proceedings of U.S. Coast Guard Vessel Stability Symposium 1993, U.S Coast Guard Academy, USA

Grimm, M., Smith, W., Fortescue, D., 2017. The Influence of Radius of Gyration Including the Effect of Inertia of Fluid on Motion Prediction. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Gu, Y., Day, S., Boulougouris, E., 2015. A Study on the Effect of Bilge Keels on Roll Damping Coefficient. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 775 – 783

Ikeda, Y., Himeno, Y., Tanaka, N., 1978a. On Roll Damping Force of Ship – Effect of Friction on Hull and Normal Force of Bilge Keels. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00401

Ikeda, Y., Komatsu, K., Himeno, Y., Tanaka, N., 1978b. On Roll Damping Force of Ship – Effect of Hull Surface Pressure Created by Bilge Keels. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00402

IMO, 2003. *Review of the Intact Stability Code: Severe Wind and Rolling Criterion (Weather Criterion)*. SLF 46/6/10, IMO, London, UK

IMO, 2006. *Interim Guidelines for Alternative Assessment of the Weather Criterion*. MSC.1/Circ.1200, IMO, London, UK

IMO, 2008. *The International Code on Intact Stability*. MSC.267(85), IMO, London, UK.

IMO, 2013. *Development of Second Generation Intact Stability Criteria: Vulnerability Assessment for Dead-ship Stability Failure Mode*. SDC 1/INF.6, IMO, London, UK

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K, 2014. Experimental and CFD Simulation of Roll Motion of Ship with Bilge Keel. *In:* Proceeding on the International Conference on Computational and Experimental Marine Hydrodynamics 2014, Chennai, 3 – 4 December, India.

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2015. CFD Approach to Roll Damping of Ship with Bilge Keel with Experimental Validation. *Applied Ocean Research*, Volume 55, pp. 1 – 17

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2017. Parametric Study on Roll Damping of Ship Midsection with Bilge Keel from Roll Decay Using CFD. *In:* Proceedings of the 5th International Conference on Ship and Offshore Technology ICSOT 2017, Kharagpur, 7 – 8 December, India.

Ishida, S., Taguchi, H., Sawada, H., 2011. *Contemporary Ideas on Ship Stability and Capsizing in Waves.* In: Neves MAS, Belenky VL, de Kat, JO, Spyrou K, Umeda N (Eds.), Springer, London, pp. 65 – 78

ITTC, 2011. Recommended Procedures: Numerical Estimation of Roll Damping. *In:* Proceedings of the 26th ITTC Specialist Committee on Stability in Waves 2011, Rio de Jeneiro, Brazil

Jiang, Y., Yeung, R.W., 2017. Bilge-keel Influence on Free Decay of Roll Motion of a Realistic Hull. *Journal of Offshore Mechanics and Artic Engineering*, Volume 139(4), pp. 041801-1 – 041801-12

Jiang, Y., Ding, Y., Sun, Y., Shao, Y., Sun, L., 2020. Influence of Bilge-Keel Configuration on Ship Roll Damping and Roll Response in Waves. *Ocean Engineering*, Volume 216, pp. 1 – 20.

Katayama, T., Matsuoka, M., Ikushima, K., 2018. Characteristics of Bilge Keel Roll Damping Component for Shallow Draft. *In:* Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles 2018, Kobe, 16 – 21 September, Japan, pp. 350 – 359

Kianejad, S.S., Enshaei, H., Ranmuthugala, D., 2017. Estimation of Added Mass Moment of Inertia in Roll Motion Through Numerical Simulation. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Kristensen, H.O., 2016. *Analysis of Technical Data of Ro-Ro Ships.* HOK Marineconsult ApS, Denmark

Papanikolaou, A., Boulougouris, E., Spanos, D., 1997. On the Roll Radius Gyration of Ro-Ro Passenger Ships. *In:* Proceedings of the Seventh International Society of Offshore and Polar Engineers (ISOPE) Conference 1997, Honolulu, 24 – 26 November, USA, pp. 499 – 507

Paroka, D., 2018. Karakteristik Geometri dan Pengaruhnya Terhadap Stabilitas Kapal Feri Ro-Ro Indonesia (Geometric Characteristics and its Impact on Stability of Indonesian Ro-Ro Ferries). *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 15(1), pp. 1 – 8

Paroka, D., Haris, A.H., Rahman, S., 2020a. Estimation of Effective Wave Slope Coefficient of Ships with Large Breadth and Draught Ratio. *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 17(1), pp. 40 – 49

Paroka, D., Asri, S., Rosmani, Hamzah, 2020b. Alternative Assessment of Weather Criterion for Ships with Large Breadth and Draught Ratio by Model Experiment: A Case Study on an Indonesian Ro-Ro Ferry. *International Journal of Maritime Engineering*, Volume 162(1), pp. 55 – 64

Sato, Y., Taguchi, H., Ueno, M., Sawada, H., 2008. An Experimental Study of Effective Wave Slope Coefficient for Two-Dimensional Model. *In:* Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships 2008, Osaka, 26 – 29 March, Japan.

Umeda, N., Sakai, M., Maki, A., Matsuda, A., 2019. Nonlinearity in the Effective Wave Slope Coefficient for a Low Freeboard Ship. *In:* Proceedings of the 28th Conference on Japan Society of Naval Architects and Ocean Engineers 2019, Nagasaki, 3 – 4 June, Japan, pp. 27 – 30

Vassalos, D., Jasionowski, A., Cichowics, J., 2003. Weather Criterion – Question and Answer. *In:* Proceedings of the Eighth International Conference on the Stability of Ships and Ocean Vehicles 2003, Madrid, 15 – 19 September, Spain, pp. 695 - 707

artikel_paroka_submission_revised_round_2

International Journal of Technology v(i)pp-pp (YYYY)
ReceivedMonth Year / Revised Month Year / Accepted Month Year

International Journal of Technology

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

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Abstract. The effect of weight distribution to 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 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 International Maritime Organization (IMO). The three-step procedure recommended by the IMO was applied. Roll decay test and roll test in regular beam wave were conducted to obtain the natural roll period, the damping factors correspond to the breadth-to-draught ratio and the bilge keels, and the effective wave slope coefficient. The damping factor corresponds to the breadth-to-draught ratio for ship with larger radius of gyration is larger than that for the ship with smaller radius of gyration. The ship with smaller radius of gyration has a larger damping factor due to bilge keels compared to the ship with 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 effective wave slope coefficient for the ship with radius of gyration equal to that obtained by the weather criterion formula was not significant. Effect of weight distribution on the weather criterion is significant for ship without bilge keels. A significant effect of bilge keels on the weather criterion occurs to the ship with weight distribution corresponds to radius of gyration coefficient closed to that obtained by the formula in the weather criterion.

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

1. Introduction

The Indonesian ro-ro ferries are used in the inter-island particularly on short-sea routes, inland, and river transportation of passengers and vehicles. The vehicles are located on the main deck and 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. These requirements result 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 collected data of ro-ro passenger ships around the world also show the breadth-to-draught ratio of approximately 2 to 7.5 (Kristensen, 2016).

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doi: 10.14716/ijtech.v0i0.0000

The 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 centre of gravity tends to be larger than the ship depth because the payload is located above the main deck.

The stability of Indonesian ro-ro ferries are assesed by using the International Code on Intact Stability of International Maritime Organization (IMO) (IMO, 2008). The weather criterion is one of the criteria applied to ro-ro ships. This criteria was developed based on ships with breadth-to-draught ratios smaller than 3.5, ratio between the vertical center of gravity and the ship draught ranges from 0.7 to 1.5 and the natural roll periods of up to 30 seconds. The values of the variables for calculating the roll angle to windward due to wave could be unappropriate when it is 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 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). The adjustment values for the effective wave slope coefficient, wave steepness for roll periods up to 30 seconds, and damping factor due to breadth-to-draught ratio for ships with breadth-to-draught ratios up to 6.5 had been proposed (IMO, 2003; Francescutto, 2015). Recently, the extension of the roll period has been adopted in the International Code on Intact Stability (IMO, 2015) but the damping factors correspond to breadth-to-draught ratio and bilge keels as well as the effective wave slope coefficient have not been changed.

The damping factor corresponds to bilge keels in the weather criterion was assumed to be depended only on the ratio between the bilge keels area and the product between the length of waterline and the ship breadth. However, the damping moment induced by the bilge keels depends on the distance between the bilge keels and the ship centre of gravity and 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 large breadth-to-draught ratio has been verified by Katayama, et al (2018). The increasing of equivalent damping moment was not linear with the increasing of height of bilge keels (Jiang, et al, 2020). Fesman, et al (2007) found that the using of bilge keels could reduce the roll angle of a ship about 30%. Therefore, the damping factor due to bilge keels given in the weather criterion results in an overestimate roll angle due to wave when it is applied to a ship with 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 damping factor in the weather criterion has never been investigated.

The others factors should be considered when the weather criterion 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 to be located near the centre 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 weight distribution of payload could have significant effects on the roll natural period, the roll damping, and the effective wave slope coefficient. However, the adjusting values of these parameters in the weather criterion are independent of weight distribution. The radius of gyration was calculated by formula given in the weather criterion. A significant error can be obtained when the formula was applied to a ship with larger breadth-to-draught ratio and large metacentric height (GM) (Borisov, et al, 2015). The effective wave slope coefficient depends on the wave frequency (IMO, 2013). The damping moment of roll can decrease due to slower roll motion associate with a larger roll natural period (Grimm, et al., 2017). The roll period increases with increasing of the total inertia of mass which is calculated based on the weight distribution. The added inertia of roll increases when the wave frequency increases (Kianejad, et al, 2017). This means that the hydrodynamics factors correspond to the weather criterion can be different due to alteration of the weight distribution. The effect of weight disribution described by variation of radius of gyration on roll motion of a ship midsection with bilge keels has been investigated by Irkal, et al (2017) but the effect on the values of parameters in the weather criterion have never been investigated.

This paper discusses the effects of weight distribution on the parameters values of weather criterion applied to an Indonesian ro-ro ferry. This is important because the weight distribution could vary on the basis of the vehicles that are transported during the operation of the vessels. The effects of the weight distribution on the hydrodynamics factors correspond to the calculation of roll angle toward windward due to the wave can be determined. The effect of bilge keels to the effective wave slope coefficient is also investigated with different weight distribution. The results can be used to develop stability criteria of ro-ro ferry which has been categorized as non-convention ships by the IMO and to extent the tabulated values of damping factors due to breadth-to-draught ratio and the 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 subject ship 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 centre of gravity to the ship draught was 1.63. These geometric characteristics were out of the range of ship data used to develop the weather criterion.

Table 1 Main information of the sample ship

Principles 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 metacenter (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
Length of bilge keels	25.50	637.5
Height of bilge keels	0.25	6.25

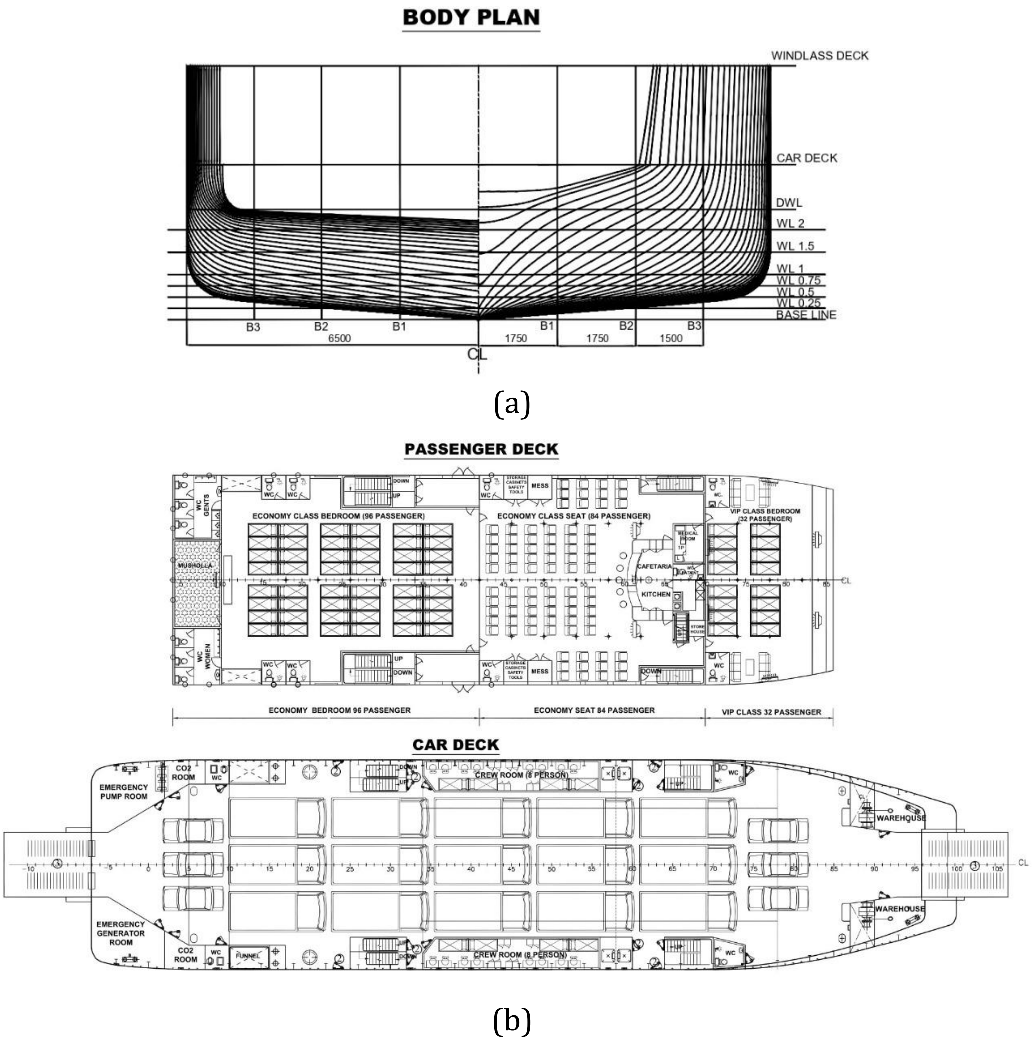


Figure 1 Desain information of the ship: (a) Body plan; and (b) Decks layout

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 accomodation was located in superstrucutre above the vehicle deck.

To investigate the effects of weight distribution, two scenarios were considered. The first scenario considered weight distribution with radius of gyration coefficient of 0.36 of ship breadth ($k_{xx} = 0.36B$). The second scenario was the weight distribution with 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 centre of gravity was kept the same for the two types of weight distribution.

2.2. Experimental Setup

The three-step procedure of model experiment recommended by IMO (IMO, 2006) was used to determined the Bertin's coefficient and the effective wave slope coefficient. Two experiments consist of roll decay test and roll test in regular beam waves are necessary to estimate the values of parameters of weather criterion formula. The model scale was 1 : 40 with model dimensions shown in Table 1. The roll decay test was conducted with the initial heel angle of 25°. The model is released to perform free roll motion and it was stopped when the roll amplitude was smaller than 0.5°. The roll angle in time domain is 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 configurations and the damping and the Bertin's coefficients were determined as average of the number of test.

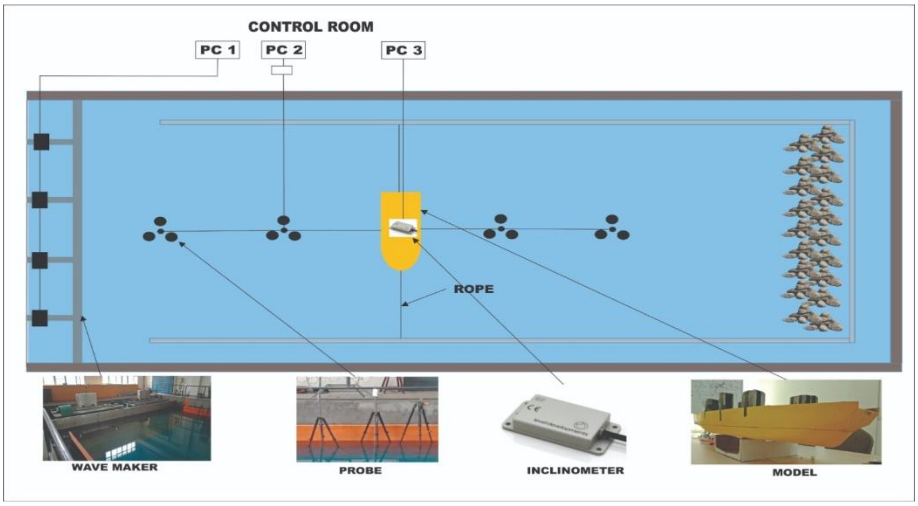


Figure 2 Model setting for experiment of roll in regular beam wave

The roll test in regular beam waves was performed for wave frequencies of 0.8, 0.9, 1.0, 1.1 and 1.2 of the roll natural frequency and the wave steepness of 0.01, 0.02, 0.03 and 0.04. The model is free in sway, heave and roll but it is restricted in surge and yaw by a flexible wire rope installed on the steam and the stern with level the same as the vertical centre of gravity as shown in Figure 2. The roll angle was measured by a dual axis inclinometer located at the midship and connected to computer (PC$_3$) for recording the roll angle in time domain. The wave profile was measured using wave probe located in front of and behind of the model. The data of wave profile is recorded in the computer (PC$_2$). The wave maker was run by using the computer (PC$_1$) with amplitude determined base on the tested frequency and steepness of wave. The actual wave steepness is calculated based on the recorded wave profile with calibration factor obtained before running the experiment. The measurement of wave profile and roll angle was started at the same time with running of the wave maker for duration of 60 seconds. The roll test was repeated twice for each test conditions. The effective wave slope coefficient are determined base on the Bertin's coefficient with extinction coefficient obtained by roll decay test, actual wave height and period measured by wave probe and the roll amplitude obtained by the roll test in regular beam wave. This roll amplitude was determined within the time duration with steady roll motion.

2.3. Data Analysis

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

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

where α $(1/s)$ and β $(1/rad)$ are the linear and quadratic damping coefficients, respectively. The roll natural frequency was designted by ω_0 (rad/s). γ_3 and γ_5 are the third and the fifth orders coefficients of polynomial equation of 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 as basic to determined the damping coefficients based on the extinction coefficient obtained by roll decay test. The order of extinction coefficients depend on the order of damping moment described in the roll motion equation.

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

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

where a and b were the extinction coefficients of roll decay. ϕ_m was the average of two consecutive roll amplitde of roll decay test (degree). These coefficients were also used to determine the linear and the quadratic damping coefficients in accordance with the International Towing Tank Conference (ITTC) (ITTC, 2011). The effective wave slope coefficient was calculated using the equation as follow (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 waves for the corresponding wave steepness. T_r and H_r were 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 wave, 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, $X_2$was 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 value of 1 for 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 ship without the bilge keels. Using the obtained damping factor due to the breadth-to-draught ratio, the damping factor corresponds to the bilge keels was determined as follow:

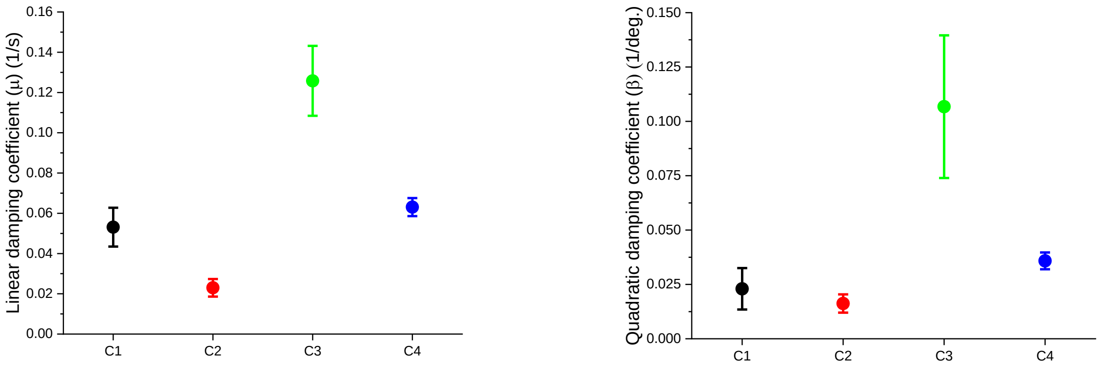
$$k = \frac{\phi_1}{109 \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s}} \tag{7}$$

The roll angle to windward due to wave was based on the results of the test in regular beam wave 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 weather criterion. A wind pressure of 300 Pa correspond to mean wind velocity of 20 m/s was used.

3. Results and Discussion

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

The linear and the 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 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 the quadratic damping coefficients.

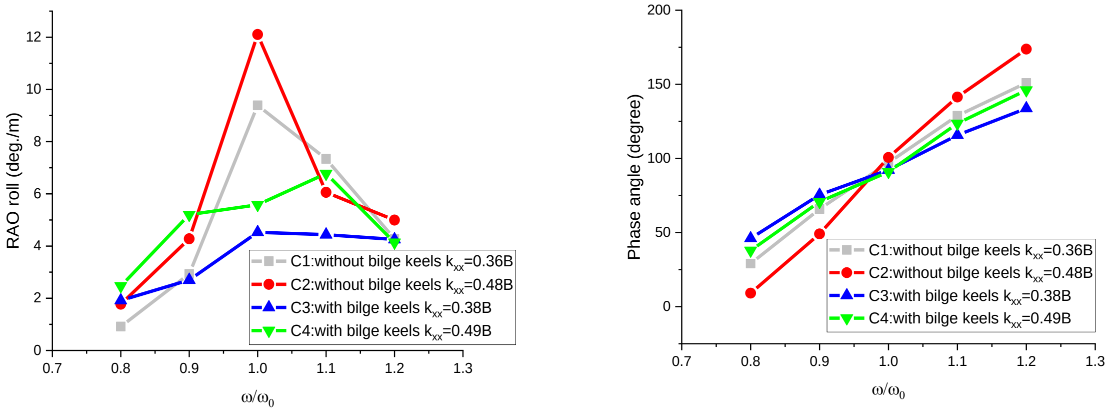


(a) (b)

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 approximately 66%. Because of the bilge keels, the quadratic damping coefficient increased about 73% for the ship with smaller radius of gyration. For the ship with a larger radius of gyration, the bilge keels increased the quadratic damping coefficient about 51%. The effect of bilge keels on the quadratic damping coefficient is larger than that on linear damping coefficient for the ship with smaller radius of gyration. Oppositely, the linear damping cofficient was more affected by the bilge keels for a larger radius of gyration. The angular velocity of roll motion decreases when the roll moment of inertia increase, therefore the damping moment decrease. Ikeda, et al (1978a) found that the normal force of bilge keels linearly increase as the roll frequency increase. Therefore the damping coefficient decrease due to increase of roll radius gyration. The effect of bilge keels on the obtained damping coefficients is larger than that obtained by Fesman, et al (2007). Results of numerical simulation 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 on not only the area of the bilge keels but also the distance from the vertical centre of gravity, especially for ships with large breadth-to-draught ratios (Katayama et al., 2018; Jiang, et al, 2020).

The different effects of the weight distribution on the damping coefficients for the ship 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 roll natural period increased by approximately 7% because of the bilge keels in the condition with a radius of gyration coefficient of 0.36B. A similiar value of increasing the natural roll period due to bilge keels has been 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 roll natural 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 increase as the radius of gyration decreased. Therefore the effect of bilge keels on quadratic damping coefficient for the ship with 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 regular beam wave: (a) RAO; and (b) Phase angle

The response amplitude operator (RAO) and phase angle of roll obtained by roll test in regular beam wave are shown in Figure 4. The RAOs of ship with larger radius of gyration were larger than those for ship with smaller radius of gyration. These results show that the equivalent damping coefficient of ship with smaller radius of gyration was larger than that for ship with larger radius of gyration as shown in Figure 3. The bilge keels was significantly affect the roll motion on the resonance frequency for both the ship with smaller and larger radii of gyration. The bilge keels effect on RAO of roll tends to decrease for the wave frequency smaller or larger than the resonance frequency. This means that contribution of bilge keels on quadratic damping coefficient was more significant compared to the bilge keels contribution on linear damping coefficient. The bilge keels effect on damping moment significantly affected by the roll amplitude and the roll frequency. The phase angle of roll tends to decrease due to decrease of damping coefficient for wave frequency smaller than the roll natural frequency. For wave frequency larger than the roll natural frequency, the phase angle increase 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. These coefficients 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 indicated that the nonlinear effect play an important role mainly for short wave-length region. A similiar results have been found for a ship with breadth-to-draught ratio of 5.83 (Sato, et al, 2008). The wave height may also have effect on the effective wave slope coefficient as the coefficient obtained for approximately constant wave length corresponding to 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 deck, especially at 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 case of radius of gyration of 0.48B.

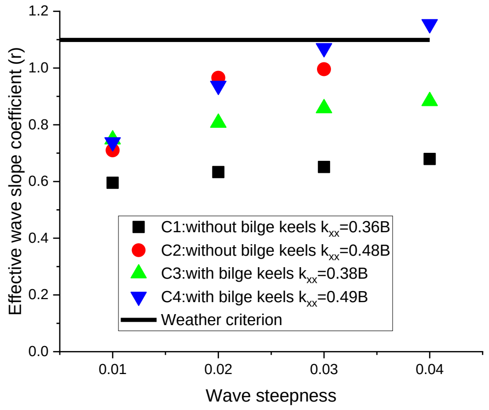


Figure 5 Effective wave slope coefficient

Regarding the smaller radius of gyration, the effective wave slope coefficient of the ship with bilge keels was larger than that without the bilge keels. In this case, the increasing of 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 obtained effective wave slope coefficients were smaller than 1.099, which was obtained with the weather criterion formula except for the ship with bilge keels and a larger radius of gyration when the wave steepness is 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 wave steepness of 0.03. This is crucial for the Indonesian ro-ro ferries because the weight distribution on the vehicle deck is based on the type of vehicles to be transported. Therefore, effect of weight distribution on the parameters values of weather criterion should be considered for the Indonesian ro-ro ferries.

The damping factors correspond to breadth-to-draught ratio and bilge keels of the subject ship were shown in Table 2. The damping factor corresponding to the breadth-to-draught ratio of the subject ship with the radius of gyration coefficient approximately the same as those obtained by the weather criterion formulae was 0.674. 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 breadth-to-draught ratio was 0.47. A smaller damping factor 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.

Table 2 The damping factors obtained by model experiments and 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

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 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 correspond to ratio between bilge keels area and product between length of waterline and breadth of 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 factors 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 smaller damping factor correspond to breadth-to-draught ratio for ship with smaller radius of gyration compared to the ship with a larger radius of gyration.

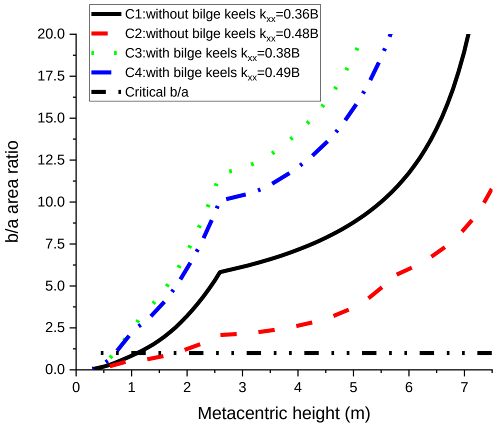


Figure 6 The b/a area ratio of weather criterion

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 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 is 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 is 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 ship both without and with 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 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 alterate between 0.793 m and 1.793 m due to variation of 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 C2 condition to be C4 condition. The increase was approximately 49% for radius of gyration of C1 condition to be C3 condition.

4. Conclusions

The damping factors correspond to the weather criterion and the effective wave slope coefficients of an Indonsian ro-ro ferry without and with 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 radius of gyration approximately the same as that calculated by weather criterion formula (0.48B) was larger than that for the ship with radius of gyration of approximately 0.36B. The damping factor corresponds to the bilge keels for the ship with radius of gyration of 0.49B was smaller compared to that for the ship with radius of gyration of 0.38B. The effective wave slope coefficient of the ship with the radius of gyration of 0.48B was larger than that of the ship with the radius of gyration of 0.36B. The formula to calculate the effective wave slope coefficient can be applied to an Indonesian ro-ro ferry if the radius of gyration equal to that calculated by the formula of 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 did not significantly affected by the bilge keels. Effect of weight distribution on the b/a area ratio of weather criterion is more significant for the ship without bilge keels compared to the ship with bilge keels. The bilge keels gives more significant contribution to the b/a area ratio in case of weight distribution with radius of gyration coefficient closed to that obtained by the formula of weather criterion. Therefore it is recommended to used model experiment as an alternative method to determined the values of parameters in the weather criterion when that criteria is applied to ships with breadth-to-draught ratio larger than 3.50 and the ratio between vertical centre of gravity and ship draught larger than 1.50.

Acknowledgements

This paper is part of the research supported by the Directorate General of Higher Education of Indonesia and Hasanuddin University: Grant No.1516/UN4.22/PT.01.03/ 2020. The authors express their sincere gratitude to the institutions for their support. The author expresses appreciation to Ardedi Yusuf for his assitance during the experiments.

References

Borisov, R., Luzyanin, A., Kuteynikov, M., Samoylov, V., 2015. An Approach to Assess the Excessive Acceleration Based on Defining Roll Amplitude by Weather Criterion Formula with Modified Applicability Range. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 601 – 612

Deakin, B., 2008. Evaluation of the Roll Prediction Method in the Weather Criterion. *International Journal of Maritime Engineering*, Volume 150(2), pp. 56 – 67

Fesman, E., Bayraktar, D., Taylan, M., 2007. Influence of Damping on the Roll Motion of Ships. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 127 – 134

Francescutto, A., 2007. The Intact Ship Stability Code: Present Status and Future Development. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 199 – 208

Francescutto, A., 2015. Intact Stability Criteria of Ships – Past, Present and Future. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 1199 – 1209

Fujino, M., Fuji, I., Hamamoto, M., Ikeda, Y., Ishida, S., Morita, T., Tanai, K., Umeda, N., 1993. Estimation of Roll Damping Coefficients and Effective Wave Slope Coefficients for Small Passenger Crafts. *In:* Proceedings of U.S. Coast Guard Vessel Stability Symposium 1993, U.S Coast Guard Academy, USA

Grimm, M., Smith, W., Fortescue, D., 2017. The Influence of Radius of Gyration Including the Effect of Inertia of Fluid on Motion Prediction. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Gu, Y., Day, S., Boulougouris, E., 2015. A Study on the Effect of Bilge Keels on Roll Damping Coefficient. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 775 – 783

Ikeda, Y., Himeno, Y., Tanaka, N., 1978a. On Roll Damping Force of Ship – Effect of Friction on Hull and Normal Force of Bilge Keels. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00401

Ikeda, Y., Komatsu, K., Himeno, Y., Tanaka, N., 1978b. On Roll Damping Force of Ship – Effect of Hull Surface Pressure Created by Bilge Keels. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00402

IMO, 2003. *Review of the Intact Stability Code: Severe Wind and Rolling Criterion (Weather Criterion)*. SLF 46/6/10, IMO, London, UK

IMO, 2006. *Interim Guidelines for Alternative Assessment of the Weather Criterion*. MSC.1/Circ.1200, IMO, London, UK

IMO, 2008. *The International Code on Intact Stability*. MSC.267(85), IMO, London, UK.

IMO, 2013. *Development of Second Generation Intact Stability Criteria: Vulnerability Assessment for Dead-ship Stability Failure Mode*. SDC 1/INF.6, IMO, London, UK

IMO, 2015. *Finalization of Second Generation Intact Stability Criteria: Information Collected by the Correspondence Group on Intact Stability Regarding Second Generation Intact Stability Criteria.* SDC 3/INF.10, IMO, London, UK

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K, 2014. Experimental and CFD Simulation of Roll Motion of Ship with Bilge Keel. *In:* Proceeding on the International Conference on Computational and Experimental Marine Hydrodynamics 2014, Chennai, 3 – 4 December, India.

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2015. CFD Approach to Roll Damping of Ship with Bilge Keel with Experimental Validation. *Applied Ocean Research*, Volume 55, pp. 1 – 17

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2017. Parametric Study on Roll Damping of Ship Midsection with Bilge Keel from Roll Decay Using CFD. *In:* Proceedings of the 5th International Conference on Ship and Offshore Technology ICSOT 2017, Kharagpur, 7 – 8 December, India.

Ishida, S., Taguchi, H., Sawada, H., 2011. *Contemporary Ideas on Ship Stability and Capsizing in Waves.* In: Neves MAS, Belenky VL, de Kat, JO, Spyrou K, Umeda N (Eds.), Springer, London, pp. 65 – 78

ITTC, 2011. Recommended Procedures: Numerical Estimation of Roll Damping. *In:* Proceedings of the 26th ITTC Specialist Committee on Stability in Waves 2011, Rio de Jeneiro, Brazil

Jiang, Y., Yeung, R.W., 2017. Bilge-keel Influence on Free Decay of Roll Motion of a Realistic Hull. *Journal of Offshore Mechanics and Artic Engineering*, Volume 139(4), pp. 041801-1 – 041801-12

Jiang, Y., Ding, Y., Sun, Y., Shao, Y., Sun, L., 2020. Influence of Bilge-Keel Configuration on Ship Roll Damping and Roll Response in Waves. *Ocean Engineering*, Volume 216, pp. 1 – 20.

Katayama, T., Matsuoka, M., Ikushima, K., 2018. Characteristics of Bilge Keel Roll Damping Component for Shallow Draft. *In:* Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles 2018, Kobe, 16 – 21 September, Japan, pp. 350 – 359

Kianejad, S.S., Enshaei, H., Ranmuthugala, D., 2017. Estimation of Added Mass Moment of Inertia in Roll Motion Through Numerical Simulation. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Kristensen, H.O., 2016. *Analysis of Technical Data of Ro-Ro Ships*. HOK Marineconsult ApS, Denmark

Papanikolaou, A., Boulougouris, E., Spanos, D., 1997. On the Roll Radius Gyration of Ro-Ro Passenger Ships. *In:* Proceedings of the Seventh International Society of Offshore and Polar Engineers (ISOPE) Conference 1997, Honolulu, 24 – 26 November, USA, pp. 499 – 507

Paroka, D., 2018. Karakteristik Geometri dan Pengaruhnya Terhadap Stabilitas Kapal Feri Ro-Ro Indonesia (Geometric Characteristics and its Impact on Stability of Indonesian Ro-Ro Ferries). *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 15(1), pp. 1 – 8

Paroka, D., Haris, A.H., Rahman, S., 2020a. Estimation of Effective Wave Slope Coefficient of Ships with Large Breadth and Draught Ratio. *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 17(1), pp. 40 – 49

Paroka, D., Asri, S., Rosmani, Hamzah, 2020b. Alternative Assessment of Weather Criterion for Ships with Large Breadth and Draught Ratio by Model Experiment: A Case Study on an Indonesian Ro-Ro Ferry. *International Journal of Maritime Engineering*, Volume 162(1), pp. 55 – 64

Sato, Y., Taguchi, H., Ueno, M., Sawada, H., 2008. An Experimental Study of Effective Wave Slope Coefficient for Two-Dimensional Model. *In:* Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships 2008, Osaka, 26 – 29 March, Japan.

Umeda, N., Sakai, M., Maki, A., Matsuda, A., 2019. Nonlinearity in the Effective Wave Slope Coefficient for a Low Freeboard Ship. *In:* Proceedings of the 28th Conference on Japan Society of Naval Architects and Ocean Engineers 2019, Nagasaki, 3 – 4 June, Japan, pp. 27 – 30

Vassalos, D., Jasionowski, A., Cichowics, J., 2003. Weather Criterion – Question and Answer. *In:* Proceedings of the Eighth International Conference on the Stability of Ships and Ocean Vehicles 2003, Madrid, 15 – 19 September, Spain, pp. 695 - 707

ME-4246 - 167-180 Hydrodynamics Factors Correspond...(Paroka et al.)_autohrs version

International Journal of Technology 12(1)167-179 (2021)
Received August 2020 / Revised October 2020 / Accepted January 2021

International Journal of Technology

http://ijtech.eng.ui.ac.id

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

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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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doi: 10.14716/ijtech.v12i1.4246

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

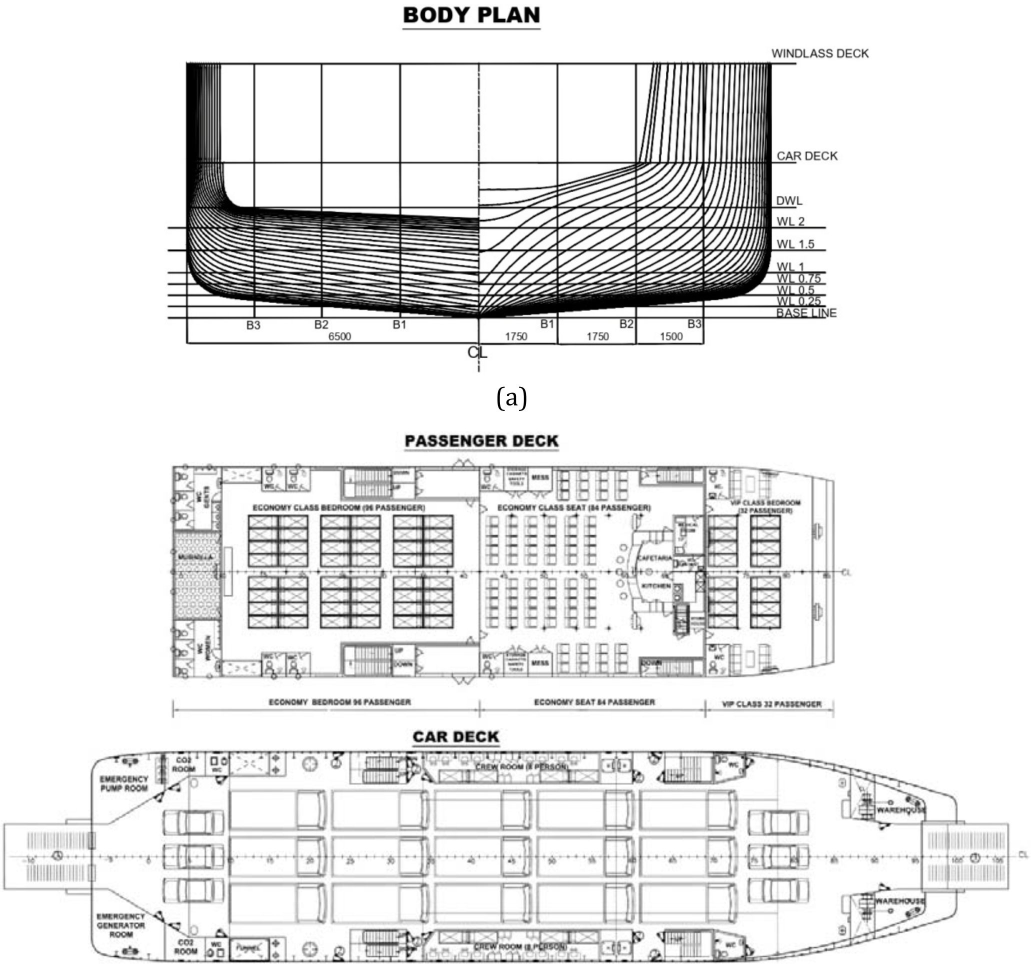
2.1. Ship Data

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.

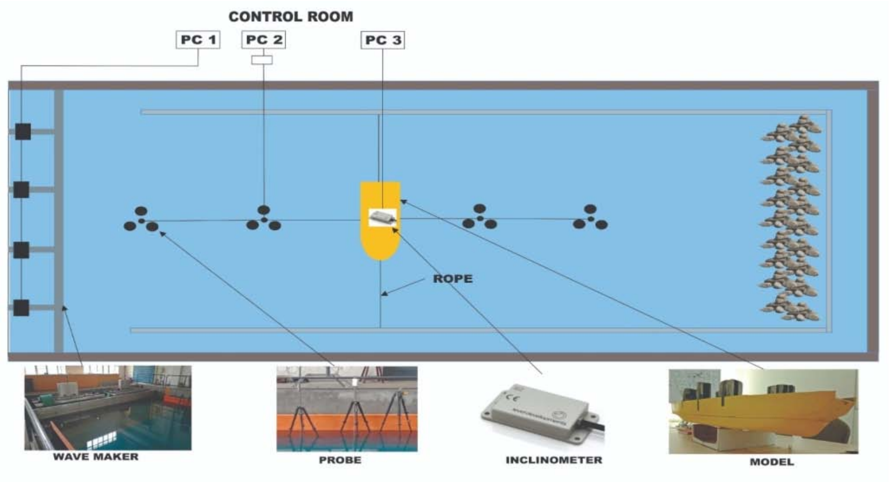


Figure 2 Model setting for roll experiment in a regular beam wave

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):

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

where $\alpha\,(1/s)$ and $\beta\,(1/rad)$ 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 $\phi_m$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:

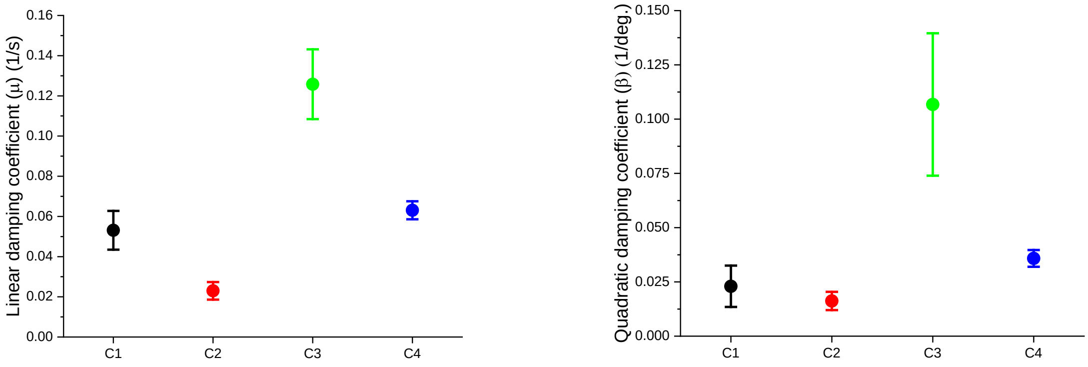
$$k = \frac{\phi_1}{109 \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s}} \tag{7}$$

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.

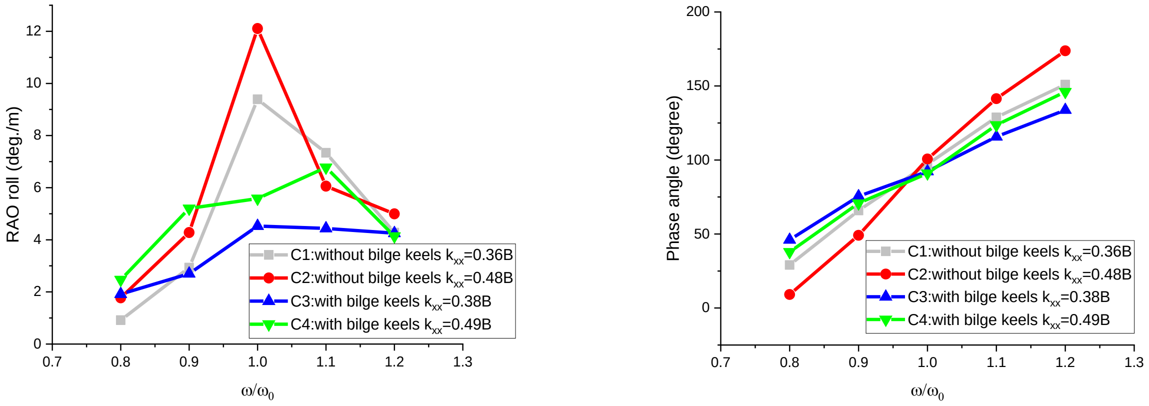


(a) (b)

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.

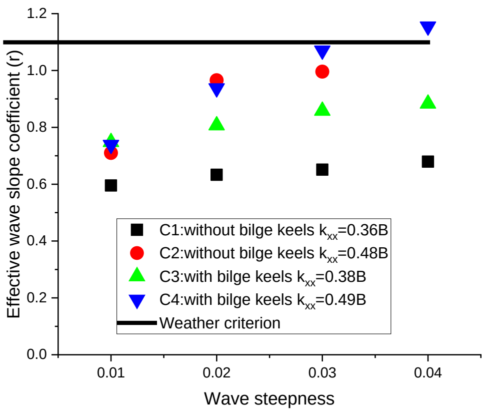


Figure 5 Effective wave slope coefficient

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.

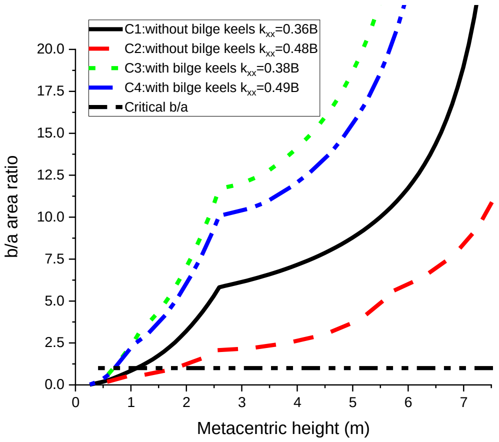


Figure 6 The b/a area ratio of the weather criterion

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.

Acknowledgements

This paper is part of the research supported by the Directorate General of Higher Education of Indonesia and Hasanuddin University: Grant No.1516/UN4.22/PT.01.03/ 2020. The authors express their sincere gratitude to these institutions for their support. The authors express appreciation to Ardedi Yusuf for his assistance during the experiments.

References

Borisov, R., Luzyanin, A., Kuteynikov, M., Samoylov, V., 2015. An Approach to Assess the Excessive Acceleration Based on Defining Roll Amplitude by Weather Criterion Formula with Modified Applicability Range. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland,pp. 601–612

Deakin, B., 2008. Evaluation of the Roll Prediction Method in the Weather Criterion. *International Journal of Maritime Engineering*, Volume 150(2), pp. 56–67

Fesman, E., Bayraktar, D., Taylan, M., 2007. Influence of Damping on the Roll Motion of Ships. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 127–134

Francescutto, A., 2007. The Intact Ship Stability Code: Present Status and Future Development. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 199–208

Francescutto, A., 2015. Intact Stability Criteria of Ships – Past, Present and Future. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 1199–1209

Fujino, M., Fuji, I., Hamamoto, M., Ikeda, Y., Ishida, S., Morita, T., Tanai, K., Umeda, N., 1993. Estimation of Roll Damping Coefficients and Effective Wave Slope Coefficients for Small Passenger Crafts. *In:* Proceedings of U.S. Coast Guard Vessel Stability Symposium 1993, U.S Coast Guard Academy, USA

Grimm, M., Smith, W., Fortescue, D., 2017. The Influence of Radius of Gyration Including the Effect of Inertia of Fluid on Motion Prediction. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Gu, Y., Day, S., Boulougouris, E., 2015. A Study on the Effect of Bilge Keels on Roll Damping Coefficient. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 775–783

Ikeda, Y., Himeno, Y., Tanaka, N., 1978a*. On Roll Damping Force of Ship – Effect of Friction on Hull and Normal Force of Bilge Keels*. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00401

Ikeda, Y., Komatsu, K., Himeno, Y., Tanaka, N., 1978b. *On Roll Damping Force of Ship – Effect of Hull Surface Pressure Created by Bilge Keels*. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00402

IMO, 2003. *Review of the Intact Stability Code: Severe Wind and Rolling Criterion (Weather Criterion)*. SLF 46/6/10, IMO, London, UK

IMO, 2006. *Interim Guidelines for Alternative Assessment of the Weather Criterion*. MSC.1/Circ.1200, IMO, London, UK

IMO, 2008. *The International Code on Intact Stability*. MSC.267(85), IMO, London, UK.

IMO, 2013. *Development of Second Generation Intact Stability Criteria: Vulnerability Assessment for Dead-ship Stability Failure Mode*. SDC 1/INF.6, IMO, London, UK

IMO, 2015. *Finalization of Second Generation Intact Stability Criteria: Information Collected by the Correspondence Group on Intact Stability Regarding Second Generation Intact Stability Criteria.* SDC 3/INF.10, IMO, London, UK

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K, 2014. Experimental and CFD Simulation of Roll Motion of Ship with Bilge Keel. *In:* Proceeding on the International Conference on Computational and Experimental Marine Hydrodynamics 2014, Chennai, 3–4 December, India.

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2015. CFD Approach to Roll Damping of Ship with Bilge Keel with Experimental Validation. *Applied Ocean Research*, Volume 55, pp. 1–17

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2017. Parametric Study on Roll Damping of Ship Midsection with Bilge Keel from Roll Decay Using CFD. *In:* Proceedings of the 5th International Conference on Ship and Offshore Technology ICSOT 2017, Kharagpur, 7–8 December, India.

Ishida, S., Taguchi, H., Sawada, H., 2011.*Contemporary Ideas on Ship Stability and Capsizing in Waves.* In: Neves MAS, Belenky VL, de Kat, JO, Spyrou K, Umeda N (Eds.), Springer, London, pp. 65–78

ITTC, 2011. Recommended Procedures: Numerical Estimation of Roll Damping. *In:* Proceedings of the 26th ITTC Specialist Committee on Stability in Waves 2011, Rio de Jeneiro, Brazil

Jiang, Y., Yeung, R.W., 2017. Bilge-keel Influence on Free Decay of Roll Motion of a Realistic Hull. *Journal of Offshore Mechanics and Artic Engineering*, Volume 139(4), pp. 041801-1–041801-12

Jiang, Y., Ding, Y., Sun, Y., Shao, Y., Sun, L., 2020. Influence of Bilge-Keel Configuration on Ship Roll Damping and Roll Response in Waves. *Ocean Engineering*, Volume 216, pp. 1–20

Katayama, T., Matsuoka, M., Ikushima, K., 2018. Characteristics of Bilge Keel Roll Damping Component for Shallow Draft. *In:* Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles 2018, Kobe, 16–21 September, Japan, pp. 350–359

Kianejad, S.S., Enshaei, H., Ranmuthugala, D., 2017. Estimation of Added Mass Moment of Inertia in Roll Motion Through Numerical Simulation. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3–5 October, Australia

Kristensen, H.O., 2016. *Analysis of Technical Data of Ro-Ro Ships.* HOK Marineconsult ApS, Denmark

Papanikolaou, A., Boulougouris, E., Spanos, D., 1997. On the Roll Radius Gyration of Ro-Ro Passenger Ships. *In:* Proceedings of the 7th International Society of Offshore and Polar Engineers (ISOPE) Conference 1997, Honolulu, 24–26 November, USA, pp. 499–507

Paroka, D., 2018.Karakteristik Geometri dan Pengaruhnya Terhadap Stabilitas Kapal Feri Ro-Ro Indonesia (*Geometric Characteristics and its Impact on Stability of Indonesian Ro-Ro Ferries*). *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 15(1), pp. 1–8

Paroka, D., Haris, A.H., Rahman, S., 2020a. Estimation of Effective Wave Slope Coefficient of Ships with Large Breadth and Draught Ratio. *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 17(1), pp. 40–49

Paroka, D., Asri, S., Rosmani, Hamzah, 2020b. Alternative Assessment of Weather Criterion for Ships with Large Breadth and Draught Ratio by Model Experiment: A Case Study on an Indonesian Ro-Ro Ferry. *International Journal of Maritime Engineering*, Volume 162(1), pp. 55–64

Sato, Y., Taguchi, H., Ueno, M., Sawada, H., 2008. An Experimental Study of Effective Wave Slope Coefficient for Two-Dimensional Model. *In:* Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships 2008, Osaka, 26–29 March, Japan.

Umeda, N., Sakai, M., Maki, A., Matsuda, A., 2019. Nonlinearity in the Effective Wave Slope Coefficient for a Low Freeboard Ship. *In:* Proceedings of the 28th Conference on Japan Society of Naval Architects and Ocean Engineers 2019, Nagasaki, 3–4 June, Japan, pp. 27–30

Vassalos, D., Jasionowski, A., Cichowics, J., 2003. Weather Criterion – Question and Answer. *In:* Proceedings of the Eighth International Conference on the Stability of Ships and Ocean Vehicles 2003, Madrid, 15–19 September, Spain, pp. 695–707

Order%20#754423 - R2-ME-4246-20201207084605 TR_CLEAN_REVISED_PAROKA

International Journal of Technology v(i)pp-pp (YYYY)
ReceivedMonth Year / Revised Month Year / Accepted Month Year

International Journal of Technology

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

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

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 worldwide also show a breadth-to-draught ratio of approximately 2 to 7.5 (Kristensen, 2016).

Comment [.1]: This is a little unclear. Consider perhaps "Indonesian ro-ro ferries are used for the inter-island transport of passengers and vehicles, particularly on short-sea and inland river routes." if doing so will not change the intended meaning.

Comment [.2]: In this work, decimals are frequently used when describing ratios. Unless this is a field-specific convention, I would recommend using one of the three standard conventions for representing ratios instead: (1) with a colon – e.g., 2:3, 8:3; (2) with words – e.g., 2 to 3, 8 to 3; or (3) with a fraction – e.g., 2/3, 8/3.

Comment [.3]: It's also possible tha the expression 2.3 to 8.3 *does* follow standard (2) above, i.e., with words. If that is the case, however, then expressions such as "draught ratios larger than 3.5" in the subsequent sentence would be unclear, as the other part of the ratio would appear to be missing. Please check the expression of ratios in this work to ensure they are accurately presented.

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.

Comment [.4]: In this instance, this should be either "These criteria were" or "This criterion was" depending on whether more than one criterion (plural) or a single criterion (singular) is intended. I changed the noun here to the singular "criterion" to match the surrounding words, both of which are singular, but please check to ensure that this is correct.

Comment [.5]: This is unclear. Do you mean "and a damping factor due to ships with breadth-to-draught ratios of up to 6.5 have been proposed"?

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 (Grimmet 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

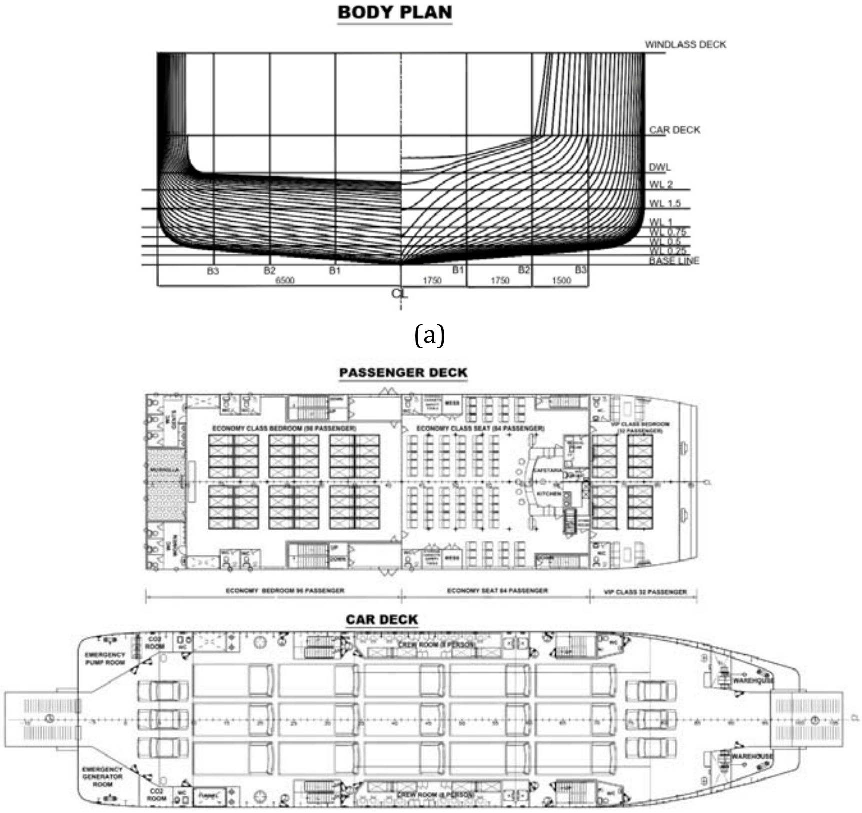
2.1. Ship Data

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

Length of 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.

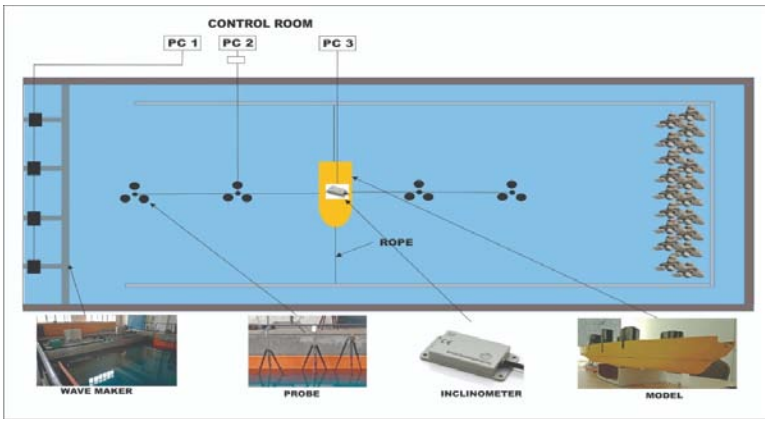


Figure 2 Model setting for roll experiment in a regular beam wave.

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):

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

where $\alpha\,(1/s)$ and $\beta\,(1/rad)$ 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 fifth order 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:

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

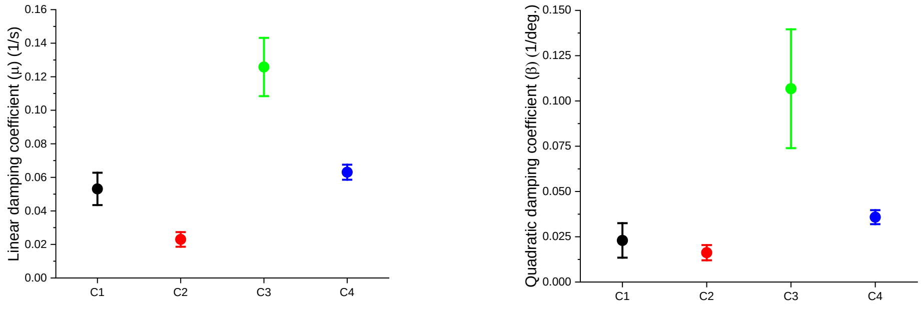
The roll angle to windward due to waves was based on the results of the regular beam wave test for the ship with the bilge keels. The obtained effective wave slope coefficient and damping factors were used to evaluate the stability of the sample ship on the basis of the weather criterion. A wind pressure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

Comment [.6]: This is a little unclear. Do you mean, perhaps, "The quadratic damping coefficients for the four ship conditions and their correspondence to linear damping coefficients 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.

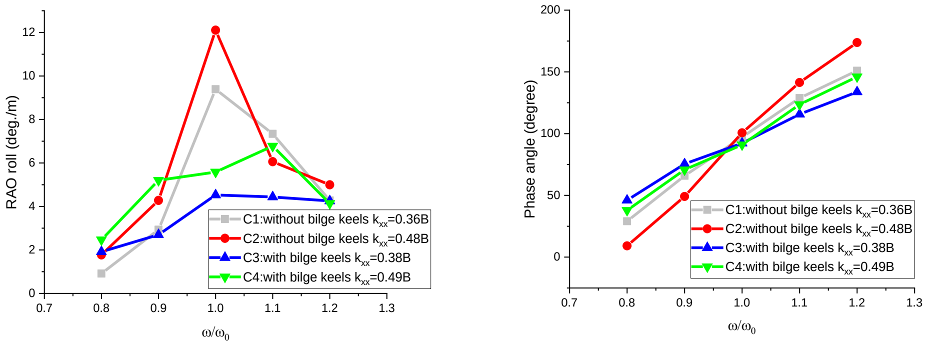


(a) (b)

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 & 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.

Comment [.7]: Do you mean "The bilge keels significantly affected the roll motion on the resonance frequency for ships with both smaller and larger radii of gyration."?

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.

Comment [.8]: Do you mean "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."?

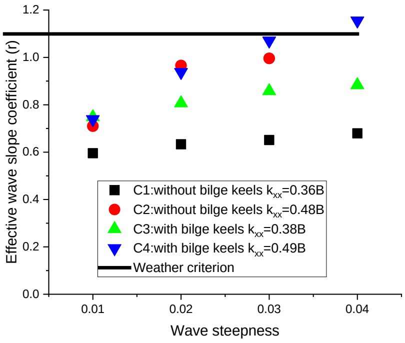


Figure 5 Effective wave slope coefficient.

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. 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.

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

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.

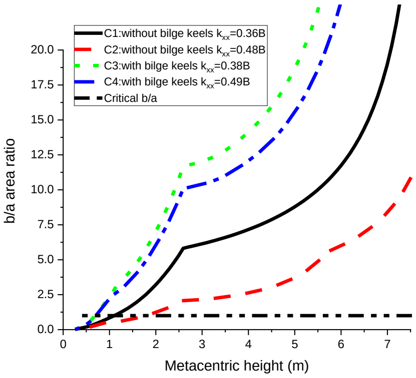


Figure 6 The b/a area ratio of the weather criterion.

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 criterion was 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.

Acknowledgements

This paper is part of the research supported by the Directorate General of Higher Education of Indonesia and Hasanuddin University: Grant No.1516/UN4.22/PT.01.03/ 2020. The authors express their sincere gratitude to these institutions for their support. The authors express appreciation to Ardedi Yusuf for his assistance during the experiments.

References

Borisov, R., Luzyanin, A., Kuteynikov, M., Samoylov, V., 2015. An Approach to Assess the Excessive Acceleration Based on Defining Roll Amplitude by Weather Criterion Formula with Modified Applicability Range. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland,pp. 601 – 612

Deakin, B., 2008. Evaluation of the Roll Prediction Method in the Weather Criterion. *International Journal of Maritime Engineering*, Volume150(2), pp. 56 – 67

Fesman, E., Bayraktar, D., Taylan, M., 2007. Influence of Damping on the Roll Motion of Ships. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 127 – 134

Francescutto, A., 2007. The Intact Ship Stability Code: Present Status and Future Development. *In:* Proceedings of the Second International Conference on Marine Research and Transportation 2007, Naples, 28 – 30 June, Italy, pp. 199 – 208

Francescutto, A., 2015. Intact Stability Criteria of Ships – Past, Present and Future. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland,pp. 1199 – 1209

Fujino, M., Fuji, I., Hamamoto, M., Ikeda, Y., Ishida, S., Morita, T., Tanai, K., Umeda, N., 1993. Estimation of Roll Damping Coefficients and Effective Wave Slope Coefficients for Small Passenger Crafts. *In:* Proceedings of U.S. Coast Guard Vessel Stability Symposium 1993, U.S Coast Guard Academy, USA

Grimm, M., Smith, W., Fortescue, D., 2017. The Influence of Radius of Gyration Including the Effect of Inertia of Fluid on Motion Prediction. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Gu, Y., Day, S., Boulougouris, E., 2015. A Study on the Effect of Bilge Keels on Roll Damping Coefficient. *In:* Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles 2015, Glasgow, 14 – 19 June, Scotland, pp. 775 – 783

Ikeda, Y., Himeno, Y., Tanaka, N., 1978a. On Roll Damping Force of Ship – Effect of Friction on Hull and Normal Force of Bilge Keels. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00401

Ikeda, Y., Komatsu, K., Himeno, Y., Tanaka, N., 1978b. On Roll Damping Force of Ship – Effect of Hull Surface Pressure Created by Bilge Keels. Report of the Department of Naval Architecture, University of Osaka Perfecture, No. 00402

IMO, 2003. *Review of the Intact Stability Code: Severe Wind and Rolling Criterion (Weather Criterion)*. SLF 46/6/10, IMO, London, UK

IMO, 2006. *Interim Guidelines for Alternative Assessment of the Weather Criterion*. MSC.1/Circ.1200,IMO, London, UK

IMO, 2008. *The International Code on Intact Stability*. MSC.267(85), IMO, London, UK.

IMO, 2013. *Development of Second Generation Intact Stability Criteria: Vulnerability Assessment for Dead-ship Stability Failure Mode*. SDC 1/INF.6, IMO, London, UK

IMO, 2015. *Finalization of Second Generation Intact Stability Criteria: Information Collected by the Correspondence Group on Intact Stability Regarding Second Generation Intact Stability Criteria.* SDC 3/INF.10, IMO, London, UK

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K, 2014. Experimental and CFD Simulation of Roll Motion of Ship with Bilge Keel. *In:* Proceeding on the International Conference on Computational and Experimental Marine Hydrodynamics 2014, Chennai, 3 – 4 December, India.

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2015. CFD Approach to Roll Damping of Ship with Bilge Keel with Experimental Validation. *Applied Ocean Research*, Volume 55, pp. 1 – 17

Irkal, M.A.R., Nallayarasu, S., Bhattacharyya, S.K., 2017. Parametric Study on Roll Damping of Ship Midsection with Bilge Keel from Roll Decay Using CFD. *In:* Proceedings of the 5th International Conference on Ship and Offshore Technology ICSOT 2017, Kharagpur, 7 – 8 December, India.

Ishida, S., Taguchi, H., Sawada, H., 2011.*Contemporary Ideas on Ship Stability and Capsizing in Waves.* In:Neves MAS, Belenky VL, de Kat, JO, Spyrou K, Umeda N (Eds.), Springer, London, pp. 65 – 78

ITTC, 2011. Recommended Procedures: Numerical Estimation of Roll Damping. *In:* Proceedings of the 26th ITTC Specialist Committee on Stability in Waves 2011, Rio de Jeneiro, Brazil

Jiang, Y., Yeung, R.W., 2017. Bilge-keel Influence on Free Decay of Roll Motion of a Realistic Hull. *Journal of Offshore Mechanics and Artic Engineering*, Volume 139(4), pp. 041801-1 – 041801-12

Jiang, Y., Ding, Y., Sun, Y., Shao, Y., Sun, L., 2020. Influence of Bilge-Keel Configuration on Ship Roll Damping and Roll Response in Waves. *Ocean Engineering*, Volume 216, pp. 1 – 20.

Katayama, T., Matsuoka, M., Ikushima, K., 2018. Characteristics of Bilge Keel Roll Damping Component for Shallow Draft. *In:* Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles 2018, Kobe, 16 – 21 September, Japan, pp. 350 – 359

Kianejad, S.S., Enshaei, H., Ranmuthugala, D., 2017. Estimation of Added Mass Moment of Inertia in Roll Motion Through Numerical Simulation. *In:* Proceedings of the International Maritime Conference 2017, Sidney, 3 – 5 October, Australia

Kristensen, H.O., 2016. *Analysis of Technical Data of Ro-Ro Ships*. HOK Marineconsult ApS, Denmark

Papanikolaou, A., Boulougouris, E., Spanos, D., 1997. On the Roll Radius Gyration of Ro-Ro Passenger Ships. *In:* Proceedings of the Seventh International Society of Offshore and Polar Engineers (ISOPE) Conference 1997, Honolulu, 24 – 26 November, USA, pp. 499 – 507

Paroka, D., 2018.Karakteristik Geometri dan Pengaruhnya Terhadap Stabilitas Kapal Feri Ro-Ro Indonesia (Geometric Characteristics and its Impact on Stability of Indonesian Ro-Ro Ferries). *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 15(1), pp. 1 – 8

Paroka, D., Haris, A.H., Rahman, S., 2020a. Estimation of Effective Wave Slope Coefficient of Ships with Large Breadth and Draught Ratio. *KAPAL: Jurnal Sains dan Teknologi Kelautan*, Volume 17(1), pp. 40 – 49

Paroka, D., Asri, S., Rosmani, Hamzah, 2020b. Alternative Assessment of Weather Criterion for Ships with Large Breadth and Draught Ratio by Model Experiment: A Case Study on an Indonesian Ro-Ro Ferry. *International Journal of Maritime Engineering*, Volume 162(1), pp. 55 – 64

Sato, Y., Taguchi, H., Ueno, M., Sawada, H., 2008. An Experimental Study of Effective Wave Slope Coefficient for Two-Dimensional Model. *In:* Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships 2008, Osaka, 26 – 29 March, Japan.

Umeda, N., Sakai, M., Maki, A., Matsuda, A., 2019. Nonlinearity in the Effective Wave Slope Coefficient for a Low Freeboard Ship. *In:* Proceedings of the 28th Conference on Japan Society of Naval Architects and Ocean Engineers 2019, Nagasaki, 3 – 4 June, Japan, pp. 27 – 30

Vassalos, D., Jasionowski, A., Cichowics, J., 2003. Weather Criterion – Question and Answer. *In:* Proceedings of the Eighth International Conference on the Stability of Ships and Ocean Vehicles 2003, Madrid, 15 – 19 September, Spain, pp. 695 - 707

List of Changes

Manuscript: Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution

Response and Revision made by Author(s)

Reviewer #1:

No	Comments	Revision/Changes
1	In the Introduction section, the background of the study has been well elaborated, particularly, in conjunction with the research of ro-ro ferries by incorporating the relevance references. Although some parameters of the damping factors have been studied by citing some references, however, the relevance study regarding the effect of bilge keels seems to be missed in this section (although it appears in the Results & Discussion section).	The bilge keels effect has been explained in the third paragraph of page 2.
2	The authors should improve references. There are some typing errors such as “dirstribution” in the third paragraph and “cetagorized” in the last paragraph.	The typing errors have been revised
3	In the Methodology section, Figure 2 is not clear. The author should show a better schematic figure and more details of obtaining the data.	Figure 2 has been improved. Additional explanations regarding the collecting data during experiment have been added in th first paragraph of page 5
4	In Table 1, the ship particulars are only the full scale of the ship, it might be better to include the ship model scale in the table.	The model scale dimensions of the ship has been added in theTable 1
5	The quality of Figure 1 is poor, unreadable, the fonts are small and not acceptable as a standard figure for a journal paper. The authors should replace and enlarge the figure and exclude any information written other than in English.	Figure 1 has been revised as recommended
6	In the Results and Discussion section, the discussion should emphasize the know-how, new finding, boundary conditions, and the underlying physics which need to be strengthened. The scope and limitation of the methods should be discussed, too.	Addtional explanations have been added at page 7 and page 8 regarding the damping coefficients, page 8 and page 9 for theeffective wave slope coefficient.
7	The roll test in beam waves was performed in the experiment for a range of wave frequencies. It would be more informative to show and discuss the amplitudes and phases of roll motion RAOs to the reader as well in conjunction with the damping factors.	The RAOs and the phases angle obtained by roll test in regular wave has been added as Figure 4 in the page 8. Some explanations regarding these results correpond to the damping coefficients obtained by roll decay tests have been added inthe second paragraph of page 8.
8	The information of legend in Figures 4 and 5 should be added in detail.	Figure 4 and Figure 5 have been changed to be Figure 5 and Figure 6, respectively. The legend of the figures has been revised.
9	In the sixth and seventh paragraphs, the authors discussed the results corresponding to the ratio of breadth-to-draught ratio and comparing to the weather criterion. However, it is not presented in any figure or table which leads to less informative to the reader.	The tabel with otained results of damping factors corresponding to breadth-to-draught ratio and corresponding to bilge keels as well as those obtained by weather criterion have been provided as shown in page 9.

10	There are some typing and grammatical errors. English can be improved.	The typing and grammatical errors have been revised in the manuscript.
11	The conclusion of the paper should be improved. The author should give the applicable scope of the conclusions of this paper.	The conclusion has been revised by including the limitation of appplicability of the present method in the last part of the conclusion
12	The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper.	References correspond to bilge keels, effective wave slope coefficient as well as effect of radius of gyration on damping moment have been including as shown in references list.

List of Changes

Manuscript: Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution

Response and Revision made by Author(s)

Reviewer #1:

No	Comments	Revision/Changes
1	In the introduction section, the bilge keel effect has been added with some references. In the revision parts, “to be depend ...” should be “to be depended ...”	The typing error of “to be depend....” has been changed to be “to be depended ...” in the paper
2	In Figure 2, the word “ROBE” should be “ROPE”.	“ROBE” has been revised to be “ROPE” in Figure 2
3	However, looking at Figure 4 – 6, to improve the readability, it still strongly recommends identifying the information of legends for example C1: without bilge keels, Kxx = 0.36B, C2: without bilge keels, Kxx = 0.48B, etc.	Legends of Figure 4 – 6 have been improved as recommended
4	Although the authors wrote K44, however, it is more common to write the radius of gyration of the roll as Kxx	The symbol k44 has been changed to be kxx in Table 2 and in the legends of Figure 4 – 6
5	In the paragraph after Figure 4, “contibution” should be “contribution”. Then, in the subsequent paragraph, “wave-negth” should be “wave-length”.	“contibution” has been revised to be “contribution” and “wave-negth” was changed to be “wave-length”

Reviewer #2:

No	Comments	Revision/Changes
1	In ship data, it is recommended to add more details concerning bilge keels. Due to the strong effect of bilge keels highlighted in the paper more information on their area and geometry can improve the significance of the paper.	The geometry consists of length and height of bilge keels has been added in Table 1. An explanantion about the rasio of bilge keels area and the product between length of waterline and breadth of ship has been added in the second paragraph of page 10
2	It is recommended to introduce the symbols of linear and quadratic damping coefficients reported in figure 3.	Symbol for the linear and quadratic damping coefficients has been added in Figure 3 and in Equation 1
3	To this end, it is suggested to introduce the adopted roll equation in the previous section.	The roll equation has been added in the first paragraph of sub section 2.3 *Data analysis* at page 5

Thank you for inviting me as a reviewer for the manuscript **#ME-4246** entitled **"HYDRODYNAMICS FACTOR CORRESPOND TO WEATHER CRITERION APPLIED TO AN INDONESIAN RO-RO FERRY WITH DIFFERENT WEIGHT DISTRIBUTION"** that was submitted to the International Journal of Technology.

My review results for the manuscript **#ME-4246** are as follows,

In this paper, the effect of weight distribution to hydrodynamics factors in the weather criterion of International Maritime Organization (IMO) was investigated. To do this, the procedure recommended by the IMO was applied i.e. roll decay test and roll test in regular beam wave to obtain the natural roll period, the damping factors correspond to the breadth-to-draught ratio, the bilge keels, and the effective wave slope coefficient. The results of the effect of weight distribution were then discussed based on the parametrical of the damping factors and compare to the weather criterion by IMO.
Overall, the work is valuable. However, the authors should address the following comments,

1. In the Introduction section, the background of the study has been well elaborated, particularly, in conjunction with the research of ro-ro ferries by incorporating the relevance references. Although some parameters of the damping factors have been studied by citing some references, however, the relevance study regarding the effect of bilge keels seems to be missed in this section (although it appears in the Results & Discussion section). The authors should improve references. There are some typing errors such as “dirstribution” in the third paragraph and “cetagorized” in the last paragraph.
2. In the Methodology section, Figure 2 is not clear. The author should show a better schematic figure and more details of obtaining the data. In Table 1, the ship particulars are only the full scale of the ship, it might be better to include the ship model scale in the table. The quality of Figure 1 is poor, unreadable, the fonts are small and not acceptable as a standard figure for a journal paper. The authors should replace and enlarge the figure and exclude any information written other than in English.
3. In the Results and Discussion section, the discussion should emphasize the know-how, new finding, boundary conditions, and the underlying physics which need to be strengthened. The scope and limitation of the methods should be discussed, too. The roll test in beam waves was performed in the experiment for a range of wave frequencies. It would be more informative to show and discuss the amplitudes and phases of roll motion RAOs to the reader as well in conjunction with the damping factors. The information of legend in Figures 4 and 5 should be added in detail. In the sixth and seventh paragraphs, the authors discussed the results corresponding to the ratio of breadth-to-draught ratio and comparing to the weather criterion. However, it is not presented in any figure or table which leads to less informative to the reader. There are some typing and grammatical errors. English can be improved.
4. The conclusion of the paper should be improved. The author should give the applicable scope of the conclusions of this paper.
5. The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper.

Thank you for sending the revised version of the manuscript ID **#R1-ME-4246** entitled "Hydrodynamics Factors Correspond to Weather Criterion Applied to an Indonesian Ro-Ro Ferry with Different Weight Distribution".

I understand the authors have addressed each comment from the reviewer as in the revised manuscript. Although the major issues have been well revised, however, after meticulously review the revised version, I will accept the manuscript after some minor problems i.e. the information of graph legends, typing, and grammatical errors in the revised parts (highlighted texts) are revised.

In the introduction section, the bilge keel effect has been added with some references. In the revised parts, "to be depend ..." should be "to be depended …"

In the methodology section, the additional explanation in obtaining the measured data have been added. Figure 1 and Figure 2 have been revised. In Figure 2, the word "ROBE" should be "ROPE".

In the results and discussion section, the revision has been made by presenting the measured results of roll motions (Figure 4), more explanations, and Table 2. However, looking at Figure 4 – 6, to improve the readability, it still strongly recommends identifying the information of legends for example C1: without bilge keels, K_{xx} = 0.36B, C2: without bilge keels, K_{xx} = 0.48B, etc. Although the authors wrote K_{44} as presented in Table 2, however, it is more common to write the radius of gyration of the roll as K_{xx}. In the paragraph after Figure 4, "contibution" should be "contribution". Then, in the subsequent paragraph, "wave-negth" should be "wave-length".

In the references section, the revision has been well made.