Journal of Ocean Engineering and Marine Energy
https://doi.org/10.1007/s40722-024-00347-9

CASE STUDY

An insight about roll damping within the second generation intact stability criteria

Nicola Petacco[1] · Andrea Pollicardo[1] · Paola Gualeni[1]

Received: 11 January 2024 / Accepted: 19 September 2024

Abstract
Despite the recognized complexity to estimate the damping influence on ship roll motion, some efficient semi-empirical methodologies have been developed along the years to this purpose. CFD methods, in principle the most appropriate tools to predict roll damping, are not a favorite option in preliminary design at present due to their implications in terms of complexity and computational time. In this paper, an integration of the semi-empirical Ikeda's simplified method has been formulated with modification of the bilge keels and lift components, following a contribution found in the literature and relevant for Ro–Ro ships. Moreover, with focus on damping evaluation, the second generation intact stability criteria (SGISc) have been investigated: the second-level vulnerability criteria for dead ship condition and parametric roll have been applied to a Ro–Ro passenger ship. Both the consolidated and the new proposed roll damping prediction methods have been implemented in order to appreciate their effects on the final outcome.

Keywords Roll damping · Empirical prediction model · second generation intact stability criteria · Parametric roll · Dead ship condition · Ro–Ro ships

1 Introduction

The prediction of ship roll motion in a seaway is computationally demanding because of its high non-linearities and coupling factors with other motions. However, it is the most relevant in the assessment of the ship safety. Roll motion, in fact, can be characterized by large roll angles with major and several non-linear effects involved. Another issue is the influence of fluid viscosity and the related phenomena, which are difficult to be integrated in the codes based on potential flow solvers but in principle very well captured by RANSE codes. As an example of the above-mentioned issues, the effect on the roll motion of the bilge keels can be considered: at large roll angle, bilge keel on one side may emerge, thus an asymmetric effect and impact loads when hitting the free surface should be taken into account (Bassler et al. 2010; Piehl 2016).

The roll damping moment can be deemed as the most relevant component of the ship roll motion. It suffers of the above-mentioned non-linear effects; therefore, the definition of an accurate prediction model is challenging. In the latest year, several numerical methods have been developed and validated (Yang et al. 2012; Miyake and Ikeda 2013; Katayama et al. 2014; Gu et al. 2016). Moreover, the adoption of RANSE codes fosters these investigations (Wilson et al. 2006; Araki et al. 2014). Despite the strong effort in the development of satisfactory numerical prediction method, it is still common to perform experimental tests to evaluate the roll damping coefficients (Irvine et al. 2004; Kristiansen et al. 2014; Handschel and Abdel-Maksoud 2015) as well as to formulate semi-empirical method (Katayama et al. 2013; Smith 2018; de Oliveira et al. 2018). Relatively simple semi-empirical methods allow to predict the ship roll damping characteristics already at early design stage. Furthermore, coefficients inhered in such methods can be tuned to replicate the roll damping behavior of specific hull shapes becoming a fast and accurate customized prediction tool. For these reasons, they are widespread in the ship design field and the most used at present also in the safety rules framework.

✉ Nicola Petacco
nicola.petacco@unige.it

Andrea Pollicardo
andrea.pollicardo@gmail.com

Paola Gualeni
paola.gualeni@unige.it

[1] DITEN, Universitá degli Studi di Genova, Via Montallegro 1, 16145 Genoa, Italy

Published online: 07 October 2024

This paper presents a semi-empirical formulation to predict the roll damping of typical volume carrier hulls, such as Ro–Ro ships. The prediction method has been formulated to be simple enough for implementation during the early design phase. In Sect. 2, a brief introduction to relevant roll damping prediction methods is provided, followed by a presentation of the proposed method. In Sect. 3, the role of roll damping within the second generation intact stability criteria is highlighted, while the application case is presented in Sect. 4. Finally, results and comments are reported in Sects. 5 and 6, respectively.

2 Roll damping prediction methods

In the following sections, current semi-empirical roll damping prediction methods are briefly commented. In particular, two simplified methods are analyzed because of their straightforward structure that makes them suitable for application during the early design phase. Taking into account these formulations, a blended prediction method will then be proposed.

2.1 Ikeda's method

One of the most popular roll damping prediction method is the original Ikeda's method (Ikeda et al. 1978; Himeno 1981). The main assumption of this method is that, in a linear formulation of the roll damping moment, the total roll damping coefficient could be divided into seven components:

- $B_{44,F}$ = frictional damping component, caused by the skin-friction stresses along the hull during the roll motion;
- $B_{44,E}$ = eddy damping component, caused by the pressure variation on the naked hull, excluding the effect of the waves and bilge keels;
- $B_{44,L}$ = lift damping component, as a consequence of the forward speed of the ship
- $B_{44,W}$ = wave damping component, which denotes the increment of the hull-pressure damping due to the presence of free surface waves, including the effect of the interaction between the waves and lift
- $B_{44,\mathrm{BKN}}$ = normal force damping component of bilge keels, which is related to the action of the normal force on the bilge keels themselves;
- $B_{44,\mathrm{BKH}}$ = hull-pressure damping component of bilge keels, corresponding to the pressure change on the hull caused by the installation of bilge keels;
- $B_{44,\mathrm{BKL}}$ = lift damping component of bilge keels, which is related to the effect of the forward speed on the bilge keels.

Ikeda's prediction method is an established semi-empirical formulation for roll damping estimation of large vessels (ITTC 2011). The formulas used in the method derive from a combination of theory and systematic model testing, using different hull shapes and two dimensional sections. However, the accuracy of Ikeda's method turned out to be unsatisfactory for unconventional vessels with high center of gravity or shallow draft (Tanaka et al. 1981). Moreover, the Ikeda's method requires a high level of ship details not always available especially during the early design stage.

2.2 Simplified Ikeda's method

The original Ikeda's method requires detailed information that might not be available or may not be easily determined in the early design stage. Therefore, a very simple prediction formula of the roll damping based on Ikeda's method has been proposed in Kawahara et al. (2009). As the case of the previous method, also in the simplified Ikeda's method the equivalent linear roll damping coefficient has been expressed by five different components: frictional, eddy making, hull lift, wave making, and bilge keel. The modified prediction formulas have been developed on the basis of the Ikeda's original method using systematic series ships derived from Taylor Standard Series. As a result, a simplified prediction method, using only the ship main characteristics and the bilge keel dimensions, has been obtained. The simplified Ikeda's method is easily applicable at the early design stage, in comparison with the original method.

2.3 Revisited Ikeda's method

A further method for the prediction of roll damping has been presented in Söder et al. (2019) with the name Revisited Ikeda's method, as a modification of the Ikeda's original method, with specific focus on modern car carriers to better represent their damping characteristics. In particular, the hull lift and the bilge keels components have been studied in a semi-empirical manner and model tests have been performed taking into account different speeds and bilge keels configurations. Moreover, the formulation of the hull lift damping component has been investigated by non-viscous CFD calculations on the case vessels. As a result, it was found that Ikeda's original method seems to underestimate the speed influence on the bilge keels damping and this may be ascribed to the low value of the lift force acting on the bilge keels considered in the original method. It has also been concluded that hull lift damping component is significantly overestimated with the original method. In this paper, it is assumed that the revisited methodology could be partially applied to ship typologies characterized by hull geometry, notable forward speeds and high value of KG similar to the vessel typology investigated by Söder et al. (2019), i.e., pure car and truck carriers.

In conclusion, the revisited method modifies the hull lift and bilge keel damping components. In relation to the Ikeda's original method, the revisited method can be summarized as reported in (1):

$$B_{44,\text{Revisite}} = B_{44,F} + B_{44,E} + B_{44,L\,\text{Revisited}} + B_{44,W} + B_{44,\text{BKN}_{\text{Revisited}}} + B_{44,\text{BKH}_{\text{Revisited}}} + B_{44,\text{BKL}_{\text{Revisited}}} \quad (1)$$

2.4 Blended Ikeda's method

From the literature review, a more appropriate formulation of the damping terms relevant to the bilge keels and the hull lift are evidenced, as far as modern volume carriers are concerned (Söder et al. 2019). In the same reference, such terms are applied in the frame of the original Ikeda's method. In this paper, an investigation of a possible improvement of the simplified Ikeda's method, by means of the introduction of the above mentioned terms, has been carried out. The application regards a Ro–Ro passenger ship that can be compared, in terms of significant parameters, to the pure car and truck carrier (PCTC) analyzed by Söder et al. (2019). An improved roll damping prediction method simple enough to be implemented in the early design phase is proposed hereafter. The new method has been renamed as Blended Ikeda's method and it combines roll damping term of both methodologies as defined in (2):

$$B_{44,\,\text{Blended}} = B_{44,F} + B_{44,E\,\text{Simplified}} + B_{44,L\,\text{Revisited}} + B_{44,W\,\text{Simplified}} + B_{44,\text{BK}\,\text{Revisited}}, \quad (2)$$

where $B_{44,\text{BK}_{\text{Revisited}}}$ is the sum of the normal force, hull pressure, and lift terms related to the bilge keel damping component as defined in the Ikeda's revisited method by Söder et al. (2019).

The proposed method introduces a simple and fast prediction technique to evaluate roll damping for vessels not well represented by the Ikeda's method, such as fast ships with a relatively high center of gravity, typical of modern volume carriers. To address these cases, the blended method combines the simplification of the simplified Ikeda's method with corrections specific to modern volume carriers, as introduced by the revisited method. In this section, the proposed blended method has been applied to the same vessels considered in the work of Söder et al. (2019). All the necessary information and geometrical parameters to apply the blended method are available in that work, except for the KG values of all ships and the C_B/C_{WA} ratio for the forebody of Vessel C. The latter has been chosen to be equal to that of Vessel A ($C_B/C_{\text{WA}} = 0.813$), since the two ships share the main dimensions. The former has been estimated from the metacentric height and using the Normand's formulation (Schneekluth and Bertram 1998) to estimate the KB and BMT parameters, as defined in (3):

$$\text{KB} = d \cdot (0.9 - 0.36 \cdot C_M) \quad (3)$$

$$\text{BM} = \frac{0.096 + 0.89 \cdot {C_{WL}}^2}{12} \cdot \frac{B^2}{d \cdot C_B}$$

where C_M (–) is the midship section area coefficient; B is the ship breadth (m); d is the ship draft (m); C_{WL} (–) is the waterplane area coefficient estimated according to (4):

$$C_{\text{WL}} = \frac{1 + 2 \cdot (C_B/\sqrt{C_M})}{3} \quad (4)$$

A comparison of the linear equivalent roll damping coefficient ζ_e evaluated with the blended and revisited methods for the set of vessels is shown in Figs. 1, 2 and 3. The validation of the blended method has been performed as a function of roll angle and forward speed. The outcomes point out that the bended method accurately reproduces the damping coefficient for Vessel C (Fig. 3). However, for Vessel A (Fig. 1) and Vessel B (Fig. 2), the blended method underestimates the damping coefficient compared to both the revisited method and model test experiments. These discrepancies may be due to incorrect tuning of the KG values and approximations in the calculation of the total equivalent linear roll damping ζ_e for Vessel A and Vessel B, as Söder et al. (2019) provides only separate damping coefficients (i.e., bare hull and bilge keel components) for these ships.

3 Roll damping within second generation intact stability criteria

The following gives a detailed description on how the simplified Ikeda's method is applied to calculate the roll damping effect in the SGISc. In particular the attention is focused on parametric roll (PR) and dead ship condition (DS) stability failures, since, among the others considered within SGISc, they are deemed as the most influenced by roll damping effect. An exhaustive explanation of the physics of these phenomena is given in Belenky et al. (2011), Umeda (2013) and Francescutto (2019). This paper refers to the version of criteria as defined in the guidelines on the SGISc and its explanatory notes (IMO 2020, 2023). It is worth mentioning that the SGISc are based on a multi-layered approach, where a first and second-level vulnerability criteria are developed and a further direct stability assessment level is provided for as well.

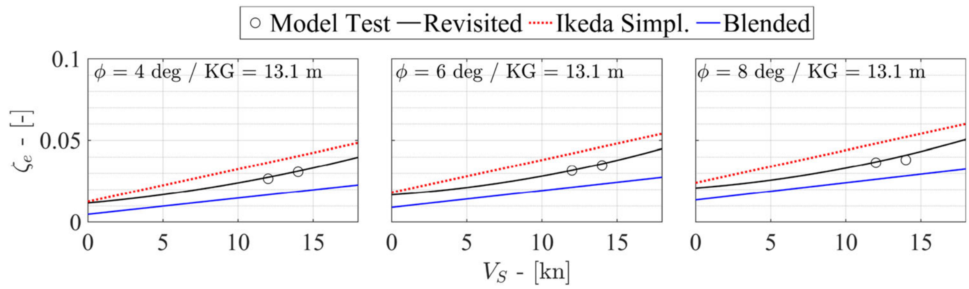

Fig. 1 Comparison between the blended and revisited method for Vessel A (Söder et al. 2019) in terms of equivalent linear roll damping coefficient as a function of ship speed and roll angle

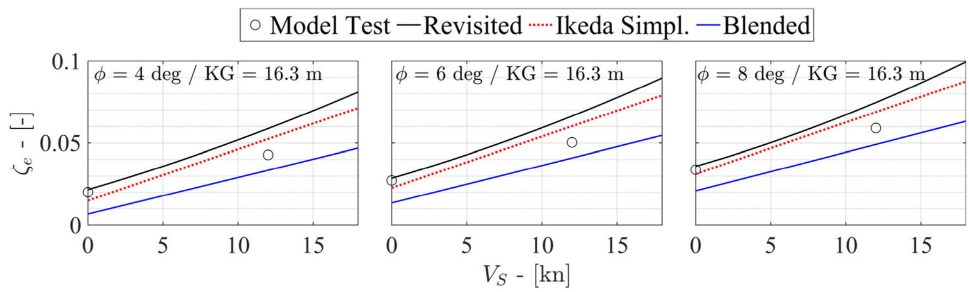

Fig. 2 Comparison between the blended and revisited method for Vessel B (Söder et al. 2019) in terms of equivalent linear roll damping coefficient as a function of ship speed and roll angle

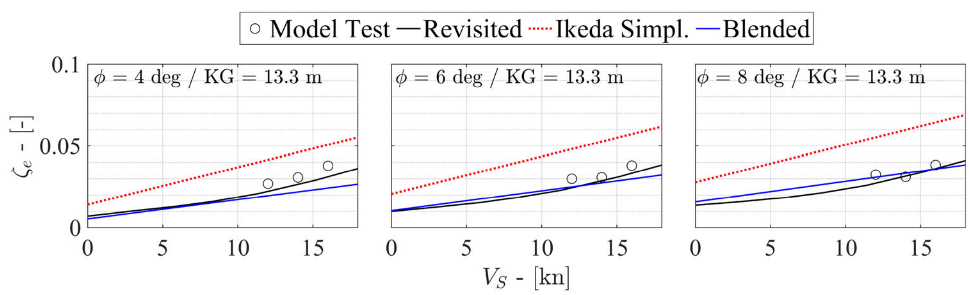

Fig. 3 Comparison between the blended and revisited method for Vessel C (Söder et al. 2019) in terms of equivalent linear roll damping coefficient as a function of ship speed and roll angle

Table 1 Ship's design characteristics

Main dimensions			
Length overall	L_{OA}	211.5	m
Length between perpendiculars	L_{BP}	186.2	m
Design draught	d	7.82	m
Depth	D	21.00	m
Breadth	B	30.40	m
Metacentric height	GM	3.50	m
Displacement	Δ	27,950	t
Block coefficient	C_B	0.62	–
Vertical distance of center of gravity	KG	13.43	m
Ship service speed	V_S	28	kn

3.1 Roll damping in the dead ship condition failure mode

In the DS stability failure mode, the ship is modeled by (5):

$$\ddot{x} + 2\mu_e(\sigma_{\dot{x}}) \cdot \dot{x} + \omega_{0,e}^2(\phi_S) \cdot x = \omega_0^2 \cdot \frac{M(t)}{W \cdot \mathrm{GM}} \tag{5}$$

where $M(t)$ is the time-dependent roll moment due to the action of waves and wind gustiness (N m); W is the ship displacement force (N); ω_0 is the natural roll frequency (rad/s); $\omega_{0,e}$ is the equivalent natural roll frequency (rad/s); GM is the upright metacentric height (m); $x = \phi - \phi_S$ is the roll angle with respect to the static heeling angle ϕ_S due to the action of mean wind (rad) and μ_e is the equivalent linear roll damping coefficient as defined in (6).

$$\mu_e(\sigma_{\dot{x}}) = \mu + \sqrt{\frac{2}{\pi}} \cdot \beta \cdot \sigma_{\dot{x}} + \frac{3}{2} \cdot \delta \cdot \sigma_{\dot{x}}^2 \tag{6}$$

Where $\sigma_{\dot{x}}$ is the standard deviation of the roll rate (rad/s); μ is the linear roll damping coefficient (1/s); β is the quadratic roll damping coefficient (1/rad) and δ is the cubic roll damping coefficient (s/rad^2). The roll damping coefficients are calculated by the following least square fitting expression (7):

$$\frac{B_{44}(\phi_a) \cdot \omega_\phi^2}{2W \cdot \mathrm{GM}} \mapsto \mu + \frac{4}{3\pi} \cdot \beta \cdot \omega_\phi \cdot \phi_a + \frac{3}{8} \cdot \delta \cdot \omega_\phi^2 \cdot \phi_a^2 \tag{7}$$

Table 2 Investigated loading conditions

Loading condition	Characterizing parameters				
	d (m)	Δ (t)	KG (m)	C_M (–)	$C_{B_{fore}}/C_{WL_{fore}}$ (–)
Departure w/truck	7.82	27,950	13.43	0.969	0.7359
Mid-voyage w/truck	7.61	26,889	13.97	0.968	0.7352
Arrival w/truck	7.00	26,041	14.44	0.967	0.7291
Departure w/car	7.40	24,246	13.20	0.968	0.7336
Mid-voyage w/car	6.74	22,800	13.72	0.966	0.7274
Arrival w/car	6.42	21,644	14.20	0.965	0.7253

where B_{44} is the equivalent linear roll damping coefficient evaluated by the simplified Ikeda's methods as function of roll angles (N m/(rad/s)).

3.2 Roll damping in the parametric rolling failure mode

In the PR stability failure, the roll motion in the 1 degree of freedom model is described by (8):

$$\ddot{\phi} + (2\alpha\dot{\phi} + \gamma\dot{\phi}^3) + \frac{W\,\mathrm{GZ}(t,\phi)}{I_{xx} + J_{xx}} = 0 \tag{8}$$

where $I_{xx} + J_{xx}$ is the transverse moment of inertia and the corresponding roll added mass term (N m); GZ(t, ϕ) is the non-linear time-dependent restoring term (m). The linear and cubic damping coefficient are calculated assuming that the roll extinction curve in calm water is represented by (9):

$$\Delta\phi = a\phi_m + c\phi_m^3 = (a + c\phi_m^2)\cdot\phi_m = a_e\cdot\phi_m \tag{9}$$

where $\Delta\phi$ is the decrement of roll decay tests (rad) and ϕ_m is the mean swing angle of roll decay test (rad), while a_e is defined in (10):

$$a_e = \frac{\alpha_e\pi}{\omega_0} = \frac{B_{44}(\phi_a)}{2(I_{xx} + J_{xx})}\cdot\frac{\pi}{\omega_0} \tag{10}$$

The procedure can be summarized as follows:

- B_{44} is calculated at roll amplitude equal to 1°. Assuming $a = a_e$ in (10), the value of a is obtained.
- B_{44} is obtained at roll amplitude equal to 25°, then the value of a_e is obtained from (10).
- c is determined by (11), where a and a_e are known and ϕ_m is equal to 25°:

$$a_e = a + c\cdot\phi_m^2 \tag{11}$$

- Finally, linear and cubic roll damping coefficients are calculated as follows:

$$\alpha = \frac{\omega_0}{\pi}\cdot a \quad \text{and} \quad \gamma = \frac{4c}{3\pi^2}\left(\frac{2\pi}{\omega_0}\right) \tag{12}$$

B_{44} is evaluated according to the simplified Ikeda's method.

4 Application case

In order to gain a further insight about the roll damping prediction methods mentioned above, a Ro–Ro passenger ship has been selected as case study (Table 1). The vessel is fitted with a pair of bilge keels having a span of $b_{BK} = 0.30$ m and a length of $l_{BK} = 65.96$ m.

To expand the investigation's scope, six representative loading conditions have been considered, as indicated in Table 2. They are referred to two different typical cargo configurations (i.e., only Trucks or only Car on the garage decks), considered at departure, mid-voyage and arrival conditions (i.e., 100%, 50% and 10% consumables respectively). In Table 2, besides displacement, draft and KG, parameters useful for the damping terms calculation are reported.

r

Two loading conditions among those selected do not fit into the applicability range of the simplified Ikeda's method in terms of beam over draft ratio (about 5% over the limit). In such cases, the extreme value of the applicability domain has been chosen in the calculation. From the design point of view, it has been interesting to investigate how ship roll damping may change using different evaluation methods, for different values of vertical center of gravity, ship forward speed and roll angles. Eventually, a comparison analysis on the outcome about ship vulnerability from SGISc application has been carried out, adopting both the simplified Ikeda's methods and the proposed blended method.

5 Calculations

In order to better understand the role of roll damping within the new SGISc, two different formulations (simplified and blended Ikeda's methods) are going to be applied with a specific focus on DS and parametric rolling failure mode. As already mentioned, these latter phenomena are the most influenced by the roll damping effect.

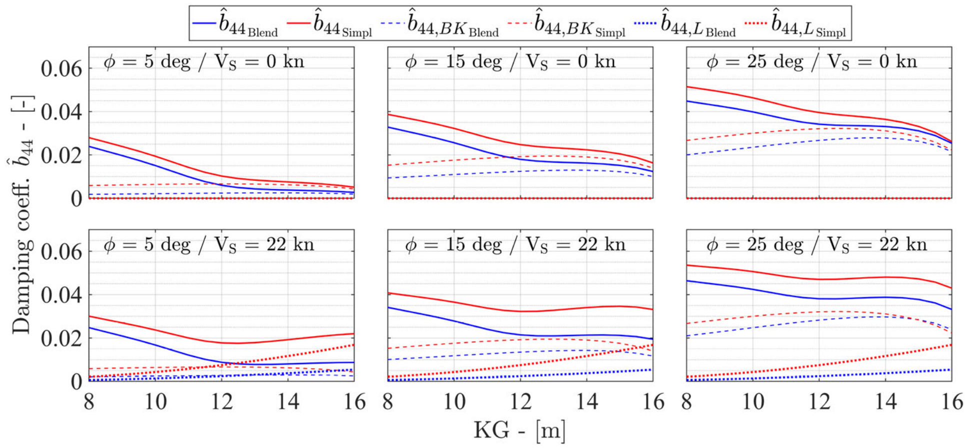

Fig. 4 Comparison between roll damping components as function of vertical position of the center of gravity KG. First row, from left to right: $\phi = 5°$ and $V_S = 0$ kn; $\phi = 15°$ and $V_S = 0$ kn; $\phi = 25°$ and $V_S = 0$ kn. Second row, from left to right: $\phi = 5°$ and $V_S = 22$ kn; $\phi = 15°$ and $V_S = 22$ kn; $\phi = 25°$ and $V_S = 22$ kn

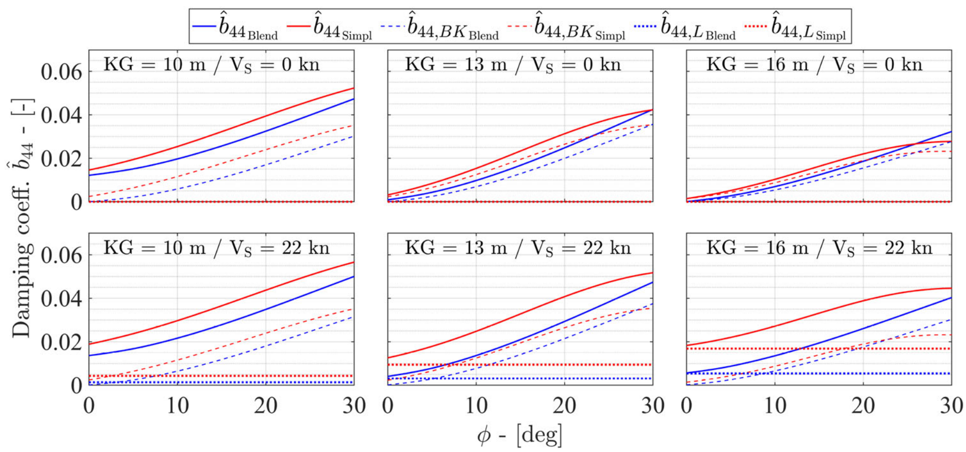

Fig. 5 Comparison between roll damping components as function of roll angles ϕ. First row, from left to right: KG = 10 m and $V_S = 0$ kn; KG = 13 m and $V_S = 0$ kn; KG = 16 m and $V_S = 0$ kn. Second row, from left to right: KG = 10 m and V_S = 22 kn; KG = 13 m and V_S = 22 kn; KG = 16 m and V_S = 22 kn

5.1 Comparison between roll damping prediction methods

In this section, the comparison between the total roll damping coefficients evaluated by the simplified and blended methods has been addressed. Since the sole differences between the two methods are the formulations of the bilge keel and hull lift components, only these terms have been additionally highlighted in the comparison of the outcomes. The analysis has been carried out considering the design loading condition of the Ro–Ro passenger ship (Table 1). The applied methods have empirical formulations based on the ship main dimensions provided in Tables 1 and 2. The results are shown in Fig. 4 as a function of KG, with ϕ and V_S as fixed parameters. In Fig. 5, the results are shown as a function of ϕ, with KG and V_S as fixed parameters. In Fig. 6, the results are shown as a function of V_S, with KG and ϕ as fixed parameters. In this investigation, the damping term is presented as a non-dimensional coefficient obtained by (13):

$$\hat{b}_{44} = \frac{B_{44}}{\rho \cdot \nabla \cdot B^2} \cdot \sqrt{\frac{B}{2 \cdot g}} \tag{13}$$

where B is the ship breadth (m), ρ is the sea water density (kg/m^3) and ∇ is the submerged hull volume (m^3).

Considering the influence of the KG on the damping components at zero-speed, it can be seen that both methods have a similar trend, although blended method seems to increase faster than the simplified one for large ϕ and V_S. Comparable values of $B_{44,\mathrm{BK}}$ are computed by the two methods for low values of roll angle, even if blended method increases faster than the simplified method when ϕ increases. Same conclusions can be drawn in case of forward speed for the bilge keel damping component. However, the bilge keel component obtained with the blended method increases faster than the simplified when ship speed increases.

In both the methods, the hull lift damping component does not depend on the roll angle, but instead, a change of either KG or V_S parameters has an almost linear directly proportional influence on such component.

5.2 Dead ship condition—level 2

Since the dead ship criterion assumes a "black out" scenario, the ship speed is zero, hence, the components of roll damping influenced by forward ship's speed are disregarded. The

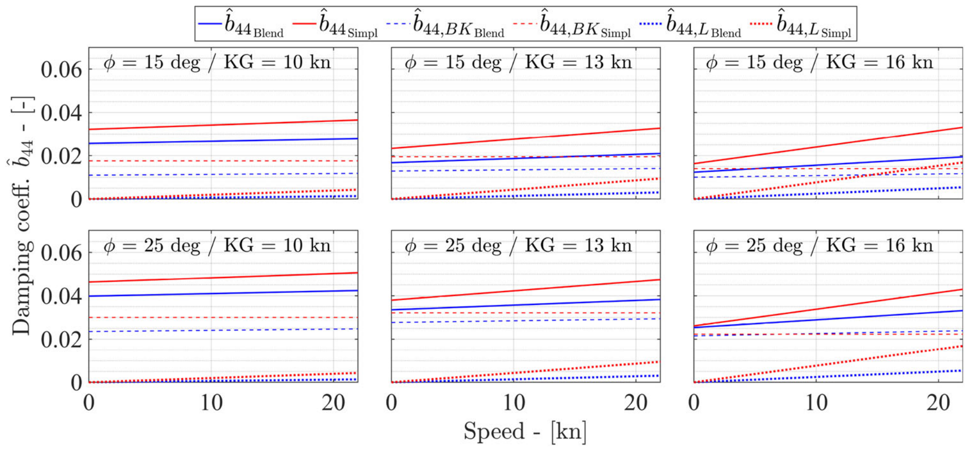

Fig. 6 Comparison between roll damping components as function of speed V_S. First row, from left to right: KG = 10 m and ϕ = 15°; KG = 13 m and ϕ = 13°; KG = 10 m and ϕ = 15°. Second row, from left to right: KG = 10 m and ϕ = 25°; KG = 13 m and ϕ = 23°; KG = 10 m and ϕ = 25°

Table 3 Application to the dead ship condition vulnerability criteria of the investigated roll damping prediction methods

Dead ship condition—2nd-level vulnerability criterion				
d (m)	Roll damping prediction method			
	Simplified		Blended	
6.42	0.00309	MET	0.00613	MET
6.74	0.00176	MET	0.00380	MET
7.00	0.00104	MET	0.00201	MET
7.40	0.00056	MET	0.00110	MET
7.61	0.00015	MET	0.00019	MET
7.82	0.00012	MET	0.00016	MET

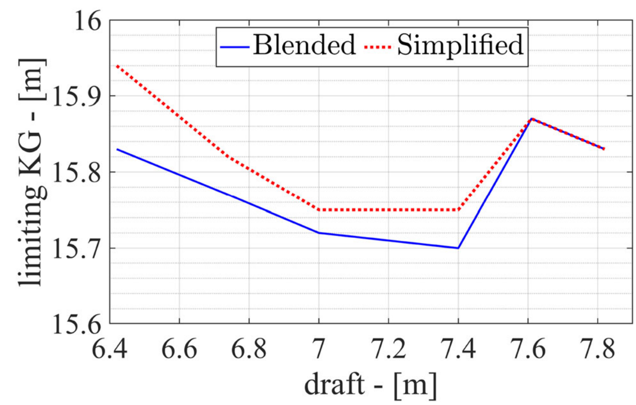

Fig. 7 Limiting KG curves for the 2nd-level vulnerability criterion of the dead ship condition

Table 4 Limiting KG values according to the dead ship condition vulnerability criteria for the investigated roll damping prediction methods

Limiting KG (m) values for the dead ship condition		
d (m)	Roll damping prediction method	
	Simplified	Blended
6.42	15.94	15.83
6.74	15.82	15.77
7.00	15.75	15.72
7.40	15.75	15.70
7.61	15.87	15.87
7.82	15.83	15.83

aim of this analysis is to assess the influence of different roll damping prediction methods on the final failure index of the second-level vulnerability of DS criterion. Applying the DS criterion requires the values of the lateral exposed area, and the vertical position of the centroid of such area. In this work, at the design loading condition (d = 7.82 m), the lateral exposed area is 5590 m^2 and its centroid is located 20.72 m above the keel line. The values have been properly adjusted according to the assessed loading condition. First, the vulnerability criterion has been applied to each loading condition, and the outcome values of each criterion are summarized in Table 3. Subsequently, an investigation on the KG limiting curves has been carried out. The comparison between the KG limiting curves evaluated applying both the simplified and the blended method is shown in Fig. 7. The drafts are reported on the horizontal axis, while KG is represented on the vertical axis. Numerical results have also been summarized in Table 4.

The direct application of the DS 2nd-level vulnerability criterion reveals a significant difference in terms of criterion between the investigated roll damping prediction methods (Table 3). The blended method yields larger values, approximately twice those obtained by the simplified method. However, the two methods converge under the deepest loading condition. Upon consideration of the criterion threshold, the failure index consistently remains below $R_{\mathrm{DS0}} = 0.06$, indicating that the vessel is not vulnerable in all the examined loading conditions. The same trend can also be noted in the definition of the limiting KG curves. Notably, there is a difference lof approximately 10 cm under the lightest loading condition, whereas the results appear to align for the heavier

Table 5 Outcomes of different roll damping methods application to the parametric roll stability failure

Parametric rolling—2nd-level vulnerability criterion				
d (m)	Roll damping prediction method Simplified		Blended	
6.42	0.0010	MET	0.0030	MET
6.74	0.0052	MET	0.0116	MET
7.00	0.0023	MET	0.0054	MET
7.40	0.0154	MET	0.0267	NOT MET
7.61	0.0183	MET	0.0235	MET
7.82	0.0216	MET	0.0325	NOT MET

loading conditions (Fig. 7). Overall, between the two methods, differences in terms of limiting KG are quite small, on the order of a few centimeters, except for the lowest drafts. This is primarily attributable to the formulation of the specific criterion: a weighted long-term analysis over a large set of sea states is conducted smoothing the differences in the final value.

5.3 Parametric rolling—level 2

The approach adopted in the previous section has been applied also to the PR stability failure. The ship vulnerability has been investigated by the second check of level 2 of parametric roll, identifying the most unfavorable loading condition, in terms of draught and relevant KG. As described in Sect. 3.2, the procedure has been applied to the selected Ro–Ro passenger ferry. The failure index has been evaluated using the two different methodologies of damping prediction. The results obtained for each loading condition, selected in the previous section, are listed in Table 5.

As expected, there is an impact of the different damping evaluation approach on the outcome of the criterion. In particular, results calculated by the blended method are higher than values provided by simplified Ikeda's approach. The difference ranges from 200 to 30%. The largest differences can be noticed when considering low draft and relatively high center of gravity. The most important implications of such evidence are that a couple of loading conditions appear to be vulnerable since the criterion results is even higher than the acceptable threshold for PR ($R_{PR0} = 0.025$).

In order to gain further insight into the role of roll damping prediction method within the PR criterion, a specific investigation has been further developed. The two different roll damping formulations provide a significantly difference on the final $C2$ criterion, therefore, they should have an influence also on the response in terms of roll angle amplitude in the time domain simulation which can be observed for a specific wave case (Fig. 8).

For this reason, the variation of the roll angle in the time domain simulations have been analyzed. Two possible scenarios have been investigated, i.e., a zero-speed condition and an encounter frequency nearly twice the natural roll frequency. The investigated speed has been calculated according to the criterion and it is equal to 17.1 kn in following waves. The wave height has been kept constant equal to 7.4 m. In Fig. 8, the numerical simulation results are reported. In the zero-speed scenario no significant differences between the damping prediction methods have been noticed. On the contrary, in the second scenario (i.e., $V_{S_1} = 17.1$ kn), there is a difference of few degrees between the two methods when large roll angle are achieved.

In addition, a comparison of the maximum roll angle achieved as a function of wave height and ship speed has been carried out. The outcomes of the analysis are shown in Fig. 9. On the horizontal axis the wave heights (h_{wave}) are reported, while on the vertical axis the maximum roll angles, achieved in the time domain simulations according to the second check criterion, are represented. The trend of the curves is similar, as expected the simplified Ikeda's method returns slightly lower maximum roll angle when compared to the blended methods. At zero-speed, the difference between the two method is very small, almost negligible. This is in line with the outcomes of Sect. 5.1, where it is shown that $B_{44,\text{ Blended}}$ is always lower than $B_{44,\text{ Simplified}}$.

In conclusion, as expected, the roll damping prediction method has a clear influence on the maximum roll angle computed by the time domain simulations within the second check of second level of parametric roll. This is reflected also on the final criterion C2, where the same loading conditions turns to be considered vulnerable or not according to the two roll damping prediction methods discussed in this paper.

It is worth to highlight that both the departure loading conditions reveal an inconsistency in the prediction methods: while the Ikeda's simplified method points out that these loading conditions are satisfied, the blended method does not. To further investigate this inconsistency, the results of the intermediate criteria for each considered sea state have been cross-compared in terms of the weighted sum of the intermediate criteria. For the departure loading condition with cars ($d = 7.40$ m), the outcomes as a function of the ship speed are reported in Table 6. The weighted sum of the intermediate criteria is defined in (14):

$$\sigma(v_S) = \sum_{i=0}^{V_S} C_{S_i}(H_S, T_Z) \cdot W_S(H_S, T_Z) \tag{14}$$

where $C_{S_i}0$ is the intermediate criterion as a function of the sea state (H_S, T_Z) and of the ship speed (v_S); W_S is the statistical weight of a sea state (H_S, T_Z) in the North Atlantic Ocean as defined in IACS (2001).

Fig. 8 Time history of roll amplitude with different roll damping prediction methods considering a regular wave with a length equal to L_{BP} and a wave height equal to 7.4 m. From left to right: V_S = 0.0 kn; V_S = 17.1 kn (following seas)

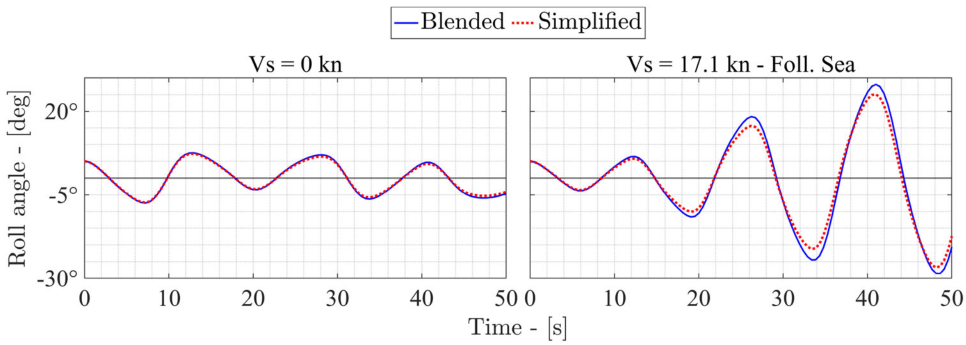

Fig. 9 Maximum roll angle achieved as a function of wave height and ship service speed. The wave length has been kept fixed equal to L_{BP}

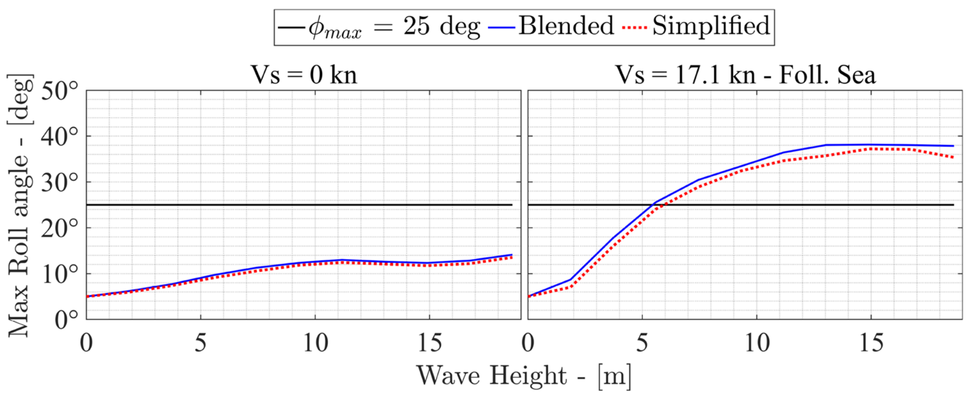

Table 6 Cross-comparison of the damping prediction method in terms of weighted sum of the intermediate criteria as a function of the ship speed

V_S	Head seas			Following seas		
(kn)	Ikeda	Blended	Difference	Ikeda	Blended	Difference
0.0	0	0	0	0	0	0
3.7	0	0	0	0	0	0
7.3	0.002	0.003	0.001	0	0	0
10.7	0.099	0.221	0.122	0	0.002	0.002
14.0	0.099	0.228	0.129	0	0	0
17.1	0.003	0.012	0.008	≈ 0	≈ 0	≈ 0
19.8	0	0	0	0	0	0
22.0	0	0	0	0	0	0
24.3	0	0	0	0	0	0
25.9	0	0	0	0	0	0
27.1	0	0	0	0	0	0
27.8	0	0	0	0	0	0
28.0	0	0	0	0	0	0

The results are referred to the departure loading condition with cars

The results indicates significant differences at intermediate speeds (between 10 and 14 kn) in heading seas. Conversely, negligible differences are observed at zero speed and following seas conditions. A similar pattern of σ has been identified for the departure loading condition with trucks ($d = 7.82$ m).

As a final analysis, the maximum wave height that ensures a maximum roll angle smaller or equal to the criterion threshold has been calculated and it is presented in Table 7. The simplified model described in the second check of second-level vulnerability assessment for PR has been used in this analysis. Only the departure loading conditions have been considered. The results show that the wave height threshold, which causes roll angles greater than 25°, is lower for sailing conditions in head seas at intermediate speeds (i.e., between 10 and 14 kn). These findings are consistent with the outcomes reported in Table 6.

Table 7 Limiting wave height ensuring a maximum roll angle lower or equal to 25° as a function of ship speed

V_S (kn)	Head seas Ikeda	Head seas Blended	Following seas Ikeda	Following seas Blended
0.00	18.6	18.6	16.8	16.8
3.67	18.6	16.8	18.6	18.6
7.25	3.7	3.7	18.6	9.3
10.72	1.9	1.9	5.6	3.7
14.00	1.9	1.9	18.6	7.4
17.05	3.7	3.7	9.3	9.3
19.80	5.6	5.6	18.6	16.8
22.20	7.4	7.4	14.9	14.9
24.25	18.6	9.3	14.9	13.0
25.87	14.9	16.8	16.8	14.9
27.05	14.9	14.9	14.9	13.0
27.75	14.9	14.9	16.8	16.8
28.00	14.9	14.9	13.0	13.0

The results are referred to the departure loading conditions with cars

6 Conclusions

The simplified version of the Ikeda's original method is a very popular methodology for roll damping estimation and it is the suggested roll damping prediction methodology within the SGISc. On the other side, a Revisited Ikeda's method has been recently developed for a more satisfactory prediction of roll damping for modern volume carriers. The focus of the revisited method was on the hull lift and bilge keels damping components. In this paper, a blended method based on the simplified Ikeda's method, where the hull lift and bilge keel terms are replaced by the once discussed by Söder et al. (2019), is proposed. To compare the simplified and blended Ikeda's method, a Ro–Ro passenger ship has been selected as application case. A systematic variation of KG, the amplitude of roll angle and the forward speed has been carried out to compare the trend of roll damping components evaluated with the two prediction methods. In general, results point out that in case of zero forward speed the simplified Ikeda's method provides slightly larger roll damping values respect to the blended method. Considering forward speeds, $B_{44,\text{ Simplified}}$ is notably larger than the blended coefficient.

As second step, the simplified and the blended Ikeda's method have been applied within the SGISc framework, in order to assess the influence of their impact on the ship vulnerability. With reference to the SGISc, the blended Ikeda's prediction method has been substituted to those proposed in the formulation of the criteria. In particular, the second-level vulnerability of DS and second check of PR have been considered. Six different loading conditions of a Ro–Ro passenger ship have been defined, i.e., the departure, the intermediate, and the arrival conditions for cargo configurations with both trucks or cars. As regards the DS, the ship is assessed as not vulnerable for all the loading conditions and for both the damping calculation methodologies. For the PR stability failure, instead, the ship appears to be vulnerable for two loading conditions when the blended method is applied. An insight on this difference has been carried out by analyzing the intermediate criteria. It points out that significant differences can be observed for heading seas between 10 and 14 kn. As regards, the DS stability failure, it is important to highlight that, while the criteria values seem to be notably affected by the roll damping prediction method, the differences seem to diminish as the draft increases in the calculation of the limiting KG curve. This may be attributable to the formulation of the 2nd-level vulnerability criteria: a weighted long-term analysis over a large set of sea states is conducted smoothing the differences in the final value.

To better investigate the role of the damping prediction methods within the PR criterion, the roll history obtained by the 1 degree of freedom model has been analyzed, considering a set of wave heights both in heading and following sea according to what defined in the criterion. Simulations for both cases of the roll damping prediction methods have been developed. The outcomes have been represented in terms of the achieved maximum roll angle as a function of wave height and ship speed. The results of the comparison between the two methods show that, for a fixed wavelength and wave height, the blended Ikeda's method returns roll angle values at high speeds that are larger than those obtained with the simplified Ikeda's method. However, the wave height threshold triggering a roll amplitude larger than 25o is similar between the damping prediction methods. The difference between the two methods becomes almost negligible at zero speed. In conclusion, the choice of the prediction method significantly affects the final results, determining whether the investigated vulnerability criterion is met or not. This points out the importance of adopting an appropriate roll damping prediction method.

Author contributions All the authors contributed equally to the conceptualization of this work. A.P. and N.P wrote the main manuscript and prepared all the figures. N.P. and P.G. reviewed the final version of the manuscript.

Funding Open access funding provided by Università degli Studi di Genova within the CRUI-CARE Agreement.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest There are no conflict of interest to be disclosed.

References

Araki M, Ohashi K, Hirata N (2014) An analysis of bilge keel effects using rans with overset grids method. In: Proceedings of 14th international ship stability workshop. Kuala Lumpur, Malaysia, pp 216–228

Bassler C, Reed A, Brown A (2010) A method to model large amplitude ship roll damping. In: Proceedings of 11st international ship stability workshop. Wageningen, The Netherlands, pp 217–224

Belenky V, Bassler C, Spyrou K (2011) Development of second generation intact stability criteria. Hydromechanics Department Report, Naval Warfare Center Carderock Division, Carderock, USA

de Oliveira M, Kassar B, Coehlo L, et al (2018) Empiricala and experimental roll damping estimates for an oil tanker in the context of the 2nd generation intact stability criteria. In: Proceedings of 13rd international conference on the stability of ships and Ocean vehicles. Kobe, Japan, pp 179–191

Francescutto A (2019) Sustainable development and innovations in marine technology, Marine Technology and Ocean Engineering series, vol 3, 1st edn. Taylor and Francis group, chap The development of second generation intact stability criteria, pp 3–8

Gu M, Bu S, Qiu G, et al (2016) Validation of CFD simulation for ship roll damping using one Pure Car Carrier and one Standard Model. In: Proceedings of 15th International Ship Stability Workshop. Stockholm, Sweden, pp 165–172

Handschel S, Abdel-Maksoud M (2015) Improvement of the harmonic excited roll motion technique for estimating roll damping. Ship Technol Res 61(3):116–130. https://doi.org/10.1179/str.2014.61.3.001

Himeno Y (1981) Prediction of ship roll damping-State of the art. Report 239, Department of Naval Architecture and Marine Engineering-University of Michigan, Michigan, USA

IACS (2001) Standard Wave Data. Recommendation n.34-Rev.1 34, International Association of Classification Society

Ikeda Y, Himeno Y, Tanaka N (1978) A prediction method for ship roll damping. Report 45. University of Osaka, Osaka, Japan

IMO (2020) Interim guidelines on the second generation intact stability criteria. Circular MSC.1/1627. International Maritime Organization, London

IMO (2023) Explanatory notes to the interim guidelines on the second generation intact stability criteria. Circular MSC.1/1652, International Maritime Organization, London

Irvine M, Longo J, Stern F (2004) Towing tank tests for surface combatant for free roll decay and coupled pitch and heave motions. In: Proceedings of 25th symposium on naval hydrodynamics. St. Johns, Canada

ITTC (2011) Numerical estimation of roll damping. Recommended procedures and guidelines 7.5-02-07-04.5. International Towing Tank Conference-Stability Committee

Katayama T, Umeda J, Hashimoto H, et al (2013) A study on roll damping estimation for non periodic motion. In: Proceedings of 13rd international ship stability workshop. Brest, France, pp 44–49

Katayama T, Yildiz B, Umeda J (2014) Numerical estimation and validation of shallow draft effect on roll damping. In: Proceedings of 14th international ship stability workshop. Kuala Lumpur, Malaysia, pp 204–209

Kawahara Y, Maekawa K, Ikeda Y (2009) A simple prediction formula of roll damping of conventional cargo ships on the basis of Ikeda's method and its limitation. In: Proceedings of 10th international conference on stability of ships and Ocean vehicles. St. Petersburg, Russia

Kristiansen T, Ruth E, Firoozkoohi R, et al (2014) Experimental and numerical investigation of ship roll damping with and without bilge keels. In: Proceedings of 33rd international conference on Ocean, Offshore and Arctic engineering. San Francisco, USA

Miyake T, Ikeda Y (2013) A study on roll damping of bilge keels for new non-ballast ship with rounder cross section. In: Proceedings of 13rd international ship stability workshop. Brest, France, pp 36–43

Piehl H (2016) Ship roll damping analysis. Ph.D. thesis, Universität Duisburg Essen, Hamburg, Germany

Schneekluth H, Bertram V (1998) Ship design for efficiency and economy, 2nd edn. Butterworth-Heinemann, Oxford

Smith T (2018) Determination of roll damping for empirical measurements. In: Proceedings of 13rd international conference on the stability of ships and ocean vehicles. Kobe, Japan, pp 301–311

Söder C, Rosén A, Huss M (2019) Ikeda revisited. J Mar Sci Technol 24:306–316. https://doi.org/10.1007/s00773-017-0497-z

Tanaka N, Himeno Y, Ikeda Y et al (1981) Experimental study on bilge-keel effect for shallow-draft ship. J Kansai Soc Nav Architects 180:69–75

Umeda N (2013) Current status of second generation intact stability criteria development and some recent efforts. In: Proceedings of 13rd international ship stability workshop. Brest, France

Wilson R, Carrica P, Stern F (2006) Unsteady RANS method for ship motions with application to roll for a surface combatant. Comput Fluids. https://doi.org/10.1016/j.compfluid.2004.12.005

Yang B, Wang Z, Wu M (2012) Numerical simulation of naval ship's roll damping based on CFD. Procedia Eng 37:14–18. https://doi.org/10.1016/j.proeng.2012.04.194