Analysis of roll damping model scale data

Citation for the original published paper (version of record):
Alexandersson, M., Mao, W., Ringsberg, J. (2021). Analysis of roll damping model scale data. Ships and Offshore Structures, 16(S1): 85-92. http://dx.doi.org/10.1080/17445302.2021.1907070

Ships and Offshore Structures

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsos20

Analysis of roll damping model scale data

Martin Alexandersson, Wengang Mao & Jonas W. Ringsberg

SHIPS AND OFFSHORE STRUCTURES
https://doi.org/10.1080/17445302.2021.1907070

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Analysis of roll damping model scale data

Martin Alexandersson [a,b], Wengang Mao [a] and Jonas W. Ringsberg [a]

[a]Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden; [b]SSPA Sweden AB, Gothenburg, Sweden

ABSTRACT
Having an accurate prediction of ship roll damping is crucial when analysing roll motions. In this paper, the simplified Ikeda method (SI-method) is compared with the original Ikeda method. The methods are compared using results from a database of roll decay tests carried out on modern merchant ships and a smaller set of predictions in which the original Ikeda method was used. It was found that most of the ships in the database had dimensions outside the limits of the SI-method. Thus, the SI-method showed poor agreement with model tests outside its limits but acceptable agreement for ships within limits. It was found that the deviations were caused by extrapolation errors of the wave-damping in the SI-method. Two ways to improve the accuracy of the SI-method were proposed based on regression, which gave about the same accuracy as the original Ikeda method.

ARTICLE HISTORY
Received 29 October 2020
Accepted 1 March 2021

KEYWORDS
Roll damping; roll decay; ikeda's method; simplified ikeda's method; ship motions

Nomenclature

ω	angular velocity of external moment rad/s
ω_0	natural angular velocity rad/s
ϕ_a	initial roll amplitude rad
A_0	mid ship area coefficient –
A_{44}	total mass moment of inertia kg*m^2
B_1	linear damping coefficient Nm/(rad/s)
B_2	quadratic damping coefficient Nm/(rad/s^2
B_3	cubic damping coefficient Nm/(rad/s)^3
B_{BK}	bilge keel roll damping Nm/(rad/s)
B_E	eddy roll damping Nm/(rad/s)
B_e	equivalen linearised damping Nm/(rad/s)
B_F	friction roll damping Nm/(rad/s)
B_L	hull lift roll damping Nm/(rad/s)
B_W	wave roll damping Nm/(rad/s)
beam	ship beam m
BK_B	bilge keel height m
BK_L	bilge keel length m
C_1	linear stiffness coefficient Nm/rad
C_3	stiffness coefficient Nm/rad^3
C_5	stiffness coefficient Nm/rad^5
C_b	block coefficient –
L_{pp}	ship perpendicular length m
OG	distance into water from still water to centre of gravity m
T	mean draught m
t	time s
V	ship speed m/s

1. Introduction

In the second generation of intact stability criteria, the IMO addressed the importance of ships having sufficient roll damping to avoid large roll motions, parametric rolling, and excessive acceleration IMO (2016). These phenomena have been well known for a very long time. Parametric roll was observed already by Froude (1861) and has been on the agenda of the marine research community since the early 1950s Galeazzi et al. (2013); it has received much more attention since (France et al. 2001) showed that the APL China casualty in 1998, where a post-Panamax C11 class container ship lost almost a third of its containers, was most likely caused by head sea parametric rolling. The damping of roll motion plays an important part during the above-mentioned phenomena, and Söder et al. (2019a) showed that the relatively small difference in the roll damping prediction they obtained with small method variation, could mean the difference between severe roll angles and hardly noticeable motions. Experimental model tests are a widely accepted method to estimate a ship's roll damping since the scale effect of the damping is mainly associated with the skin friction on ship hulls, and this friction contributes very little to a full-scale ship's total roll damping (IMO 2006). With the rapid increase in computation capability, computational fluid dynamics (CFD) methods have also been used to calculate roll damping, as in Kristiansen et al. (2014) and Piehl (2016). However, in the early stage of ship design, sometimes neither CFD methods nor experimental model tests are attractive options. For instance, when only limited information is available, such as the ship's principal dimensions and the basic hull geometry, using CFD or model tests does not make sense. Also, when doing many design iterations, CFD or model tests can be too expensive and time consuming. Therefore, simpler methods are widely used in these cases. Several semi-empirical methods were proposed in the late 1970s (Himeno 1981). The most recognised method was developed in a series of research articles (Ikeda 1978b, 1978a, 1979a; Ikeda et al. 1978; Ikeda 1979b), often referred to as Ikeda's method and based on strip theory-analysis. This semi-empirical method is also recommended by ITTC (2011). There also exists a newer and simplified version of Ikeda's method (Kawahara et al. 2011) (named the SI-method here) where, unlike in

CONTACT Martin Alexandersson maralex@chalmers.se Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg 41296, Sweden; SSPA Sweden AB, Gothenburg 41296, Sweden

Ikeda's original method, strip-theory calculations are not needed, which makes it much easier to use in the design stages of ships. This method was developed as a regression on calculation results from Ikeda's method for a series of parameterised hull shapes and is claimed (Kawahara et al. 2011) to have almost the same accuracy as the original method within its limits. Ship designs have, however, evolved since the 1970s when Ikeda's method was developed. So, the authors of the present paper wanted to see if these methods are still valid for newer ship geometries. The main objective of this paper is therefore to investigate the accuracy of the SI-method (being the newer and simplified version of Ikeda's method) using a database of more than 250 roll decay model tests. The ships from these tests are recognised as being representative of modern merchant ships that have been tested at SSPA during the past 15 years, including, for instance, oil tankers, LNG tankers, passenger ships, car carriers, and others. Furthermore, possible ways to improve the accuracy of the SI-method for these ships will be investigated.

To make the paper complete, the conducted work according to Figure 1 is divided in Section 2, which presents the basic governing equations of roll motions and how roll damping can be obtained from roll decay tests and the SI-method. Based on the roll decay test database, different methods to estimate roll damping are compared in Section 3.2. Section 4 proposes two new regression-based methods to improve the accuracy of roll damping in comparison to the SI-method. Conclusions are given in Section 5.

2. Methods for prediction and analysis of roll damping

In order to compare the SI-method with data from roll-decay model tests, methods to extract roll damping from tests and the SI-method are first examined. The roll moment along a longitudinal axis though the centre of gravity can be expressed according to Himeno (1981) by,

$$A_{44}\ddot{\phi} + B_{44}(\dot{\phi}) + C_{44}(\phi) = M_{44}(\omega t) \tag{1}$$

where A_{44} is the total mass moment of inertia, including both ship mass and virtual added mass; B_{44} is the roll damping moment (which is of primary interest in this study) and C_{44} is the restoring moment. M_{44} represents the external moment (usually moment from external waves). For small roll angles, the restoring moments $C_{44}(\phi)$ can be linearised to $C_1\phi$. To model the nonlinear restoring moments, $C_{44}(\phi)$ can be described by nth order polynomials as

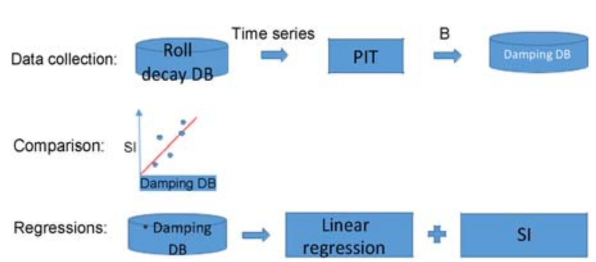

Figure 1. Overview of the work conducted for this paper. (This figure is available in colour online.)

$C_{44}(\phi) = C_1\phi + C_2\phi^2 + C_3\phi^3 + , \ldots, C_n\phi^n$ Different experimental test methods are available to determine the coefficients in Equation (1). Ikeda et al. (1978) used forced motion tests in which the roll moment was measured for models that were forced to an oscillating roll motion at various frequencies. In this paper, the model scale roll decay tests are used (more information in section 2.2). For these tests, the frequency of motion is an output rather than an input (as in the forced motion tests). Since there are no external forces in such tests, the external moment in Equation (1) is zero and the governing equation of the tests becomes,

$$A_{44}\ddot{\phi} + B_{44}(\dot{\phi}) + C_{44}(\phi) = 0 \tag{2}$$

where B_{44} can be expressed as expansion series: $B_{44} = B_1 \cdot \dot{\phi} + B_2 \cdot \dot{\phi}|\dot{\phi}| + B_3 \cdot \dot{\phi}^3 + \cdots + B_n \cdot \dot{\phi}^n$. Most often, the so-called 'linear model', 'quadratic model' and 'cubic model' are used to represent $B_{44}(\dot{\phi})$ in Equation (2) by truncating the series to keep only linear, quadratic and cubic terms,

$$A_{44}\ddot{\phi} + B_1\dot{\phi} + C_1\phi = 0 \tag{3}$$

$$A_{44}\ddot{\phi} + C_1\phi + \left(B_1 + B_2\left|\dot{\phi}\right|\right)\dot{\phi} = 0 \tag{4}$$

$$\begin{aligned} A_{44}\ddot{\phi} &+ \left(B_1 + B_2\left|\dot{\phi}\right| + B_3\dot{\phi}^2\right)\dot{\phi} \\ &+ \left(C_1 + C_3\phi^2 + C_5\phi^4\right)\phi \\ &= 0 \end{aligned} \tag{5}$$

where B_1, B_2 and B_3 are recognised as the roll damping coefficients. From roll decay tests, those coefficients are normally derived based on the logarithmic decrements of roll peaks. However, this approach is sensitive to low-frequency disturbances and measurement noise. An alternative and more robust approach, which utilises a full time series of roll decay tests and not just the peaks, is the numerical Parameter Identification Technique (PIT) as described in IMO (2006) and also used by Bulian and Francescutto (2004). In this approach, a numerical solution to a one degree of freedom roll equation is fitted to the roll decay time series by tuning the parameters in the roll equation.

2.1. Estimation of roll damping from roll decay tests

The roll decay test has the benefit that both roll damping and the natural frequency ω_0 can be observed, but it has the drawback that roll damping at only this one frequency can be obtained. In order to extract roll damping parameters from the roll decay tests, parameters in the cubic, quadratic, or linear roll decay models should be identified. The roll angle is measured during the roll decay tests. The system identification is defined as finding the parameters that produce a simulated roll signal that best fits the roll decay test measurement.

Two different solution approaches have been investigated for the system identification, i.e. the 'derivation approach' (referred to as PIT in IMO 2006) and the 'integration approach' which is similar to what Söder et al. (2019b) used. In the derivation approach, the first and second roll time derivatives are calculated numerically so that the parameters in the models are the only unknowns, and the optimal parameters that give the best fit can simply be determined using a least square fit. In the integration approach, the parameters are found by solving a nonlinear problem using the least-square method. This approach requires that an ordinary differential equation be solved for many 'guessed' sets of parameters until the solution converges.

It should be noted that even though the approach could well handle roll equations with higher order of non-linearities in the damping term as well as a non-linear restoring term, the limited amplitudes at which the roll decay tests were conducted cannot motivate advantages of higher order models. A validation of the developed parameter identification method has been conducted by checking that parameters from simulated signals with the linear, quadratic and cubic model (where the parameters are already known) can be identified correctly. The goodness of fit is described using the coefficient of determination:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{6}$$

where y_i, $\bar{y}$, $\hat{y}_i$ represents the motion angle ϕ, mean of ϕ from the model tests and estimated ϕ by the system identification method, while they represent the damping coefficients in Section 3.

2.2. Database of roll decay tests

Roll-decay model tests are normally performed prior to other dynamic tests, such as manoeuvring or seakeeping model tests, to check the properties of the tested ship model. In this study, results from such tests, carried out at SSPA in Sweden (www.sspa.se) have been used. The roll-decay tests are conducted by forcing the model to an initial roll angle and then releasing it to oscillate freely in six degrees of freedom. The tests are conducted either at zero speed or at speed without autopilot. The scaled ship models are from 3 to 6 m in length. The measurement accuracy of these model tests is very good. When time series from 20 sets of repeated tests were investigated the average R^2 was found to be 0.995. The tests were originally conducted in connection with commercial projects for buildings new merchant ships. In this study, data collected from 2005 to 2018 were used to construct the roll-decay test database, which was applied to build a roll damping database. The ship types in the roll-decay tests used in this paper are shown in Figure 2, and the main parameters of these ships

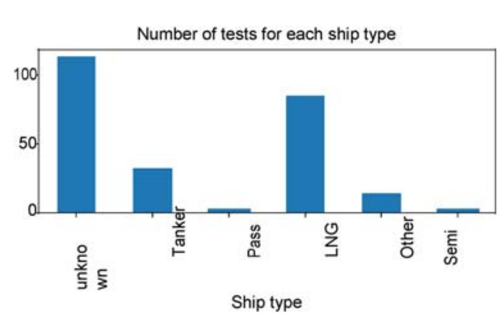

Figure 2. Number of tests per ship type. (This figure is available in colour online.)

are presented in the sensitivity study as in Figure 6. The parameter identification technique was used to estimate the roll damping coefficients from the roll-decay tests. It was investigated whether the linear model Equation (3), quadratic model Equation (4) or cubic model Equation (5) was best suited to describe the roll damping in all the tests to formulate the roll damping database. After the parameters were identified, the corresponding roll motions were simulated by the three mentioned models. The accuracy of the three models was evaluated with the R^2 score coefficient, based on model test and simulation time series of roll motions. The average R^2 was 0.995 for the cubic model, 0.993 for the quadratic, and 0.986 for the linear model. Figure 3 displays a linear, a quadratic and a cubic model fitted to one roll decay model test. It is obvious that the linear model, being a straight line in Figure 3(b), under predicts the damping for large angles and over predicts it for small angles, as can be seen in Figure 3(b). Since the quadratic model has almost the same accuracy as the cubic model, it was selected to estimate roll damping from all the roll-decay tests in the database. All the extracted roll damping coefficients together with various ship related information will be formulated as the roll damping database for the following analysis.

2.3. Ikeda's method: from strip-theory to semi-empirical formulas

Ikeda's method divides roll damping into five damping components: the friction component B_F, the eddy component B_E, the lift component B_L, the wave component B_W and the bilge keel component B_{BK}, as in the following Equation (7),

$$B_{44} = B_F + B_E + B_L + B_W + B_{BK} \tag{7}$$

where the wave and eddy components require strip-theory based hydrodynamic analysis to obtain the ship's shape coefficients. The hydrodynamic analysis requires the ship's exact hull geometries. It might be time consuming to build the geometry model and perform the strip-theory based hydrodynamic analysis. Sometimes, a ship's hull geometry is simply not available for such purposes.

A simplified Ikeda method (SI-method) was proposed by Kawahara et al. (2011) and is used in this study to calculate all the damping components including the eddy component B_E and wave component B_W. The semi-empirical formulas

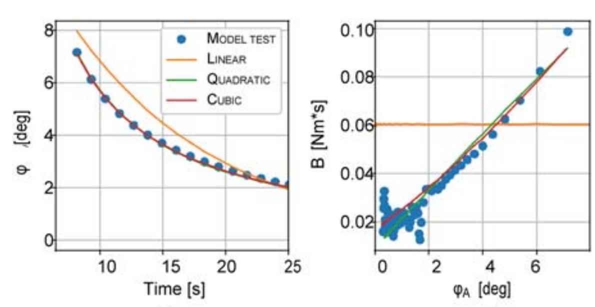

Figure 3. Roll decay model test, linear-, quadratic- and cubic-model. (a) Amplitude decrements and (b) Dampings. (This figure is available in colour online.)

describe four of the five roll damping components at motion frequency ω for a given roll amplitude ϕ_a at zero ship speed. A speed dependency was introduced by adding a fifth damping term B_L and a speed correction to B_W and B_E as described in Ikeda (1979b), giving a function:

$$\begin{aligned}(B_F,\ B_W,\ B_E,\ B_{BK},\ B_L) \\ = f\left(L_{pp}, beam, C_b, A_0, OG, \phi_a, BK_L, BK_B, \omega, T, V\right)\end{aligned} \tag{8}$$

The formulas within f can be referred to Ikeda (1979b); Kawahara et al. (2011) with the implementation in the paper by Alexandersson (2020). It should be noted that this method may be only efficiently used to estimate the roll damping of ships within the boundaries (Kawahara et al. 2011):

$$\begin{cases} 0.5 \leq C_b \leq 0.85, \quad 0 \leq \hat{\omega} \leq 1.0, \quad 0.9 \leq A_0 \leq 0.99, \\ 2.5 \leq Beam/T \leq 4.5, \quad 0.01 \leq BK_B/Beam \leq 0.06, \\ -1.5 \leq OG/T \leq 0.2, \quad 0.05 \leq BK_L/L_{PP} \leq 0.4. \end{cases} \tag{9}$$

3. Accuracy of current methods for predicting roll damping

It was shown by Kawahara et al. (2011) that Ikeda's method does not work for some modern ships with buttock flow sterns. Söder et al. (2019b) also showed that Ikeda's method was not capable of accurately predicting the roll damping for a Pure Car and Truck Carrier. The SI-method being a simplified version of Ikeda's method most likely inherits its problems but also introduces some extrapolation errors as reported by Rudaković (2017). In the following, 227 existing roll decay model tests conducted at SSPA Maritime Dynamics Laboratory are used to validate the SI-method. The comparison will help identify the drawbacks and improvement potentials of the SI-method. It aims at further developing this method to increase its accuracy through some statistical regression analysis based on the large test database.

3.1. Overall accuracy of the simplified Ikeda method

Comparing roll damping is a bit difficult since the roll damping model consist of two coefficients: a linear term B_1 and a quadratic term B_2. These coefficients can, however, be combined by calculating the equivalent damping coefficient for a certain roll angle ϕ_a (Himeno 1981):

$$B_e = B_1 + \frac{8 B_2 \omega_0 \phi_a}{3\pi} \tag{10}$$

For the roll damping database B_1 and B_2 can be inserted directly into Equation (10) to get the equivalent roll damping B_e. In order to obtain the same coefficients for the SI-method, roll damping was calculated for two roll amplitudes ϕ_a for the same motion frequency. B_1 and B_2 are obtained by fitting Equation (10) to this data Himeno (1981). The B_e coefficient was made non-dimensional according to Himeno (1981), giving the non-dimensional equivalent linear damping coefficient $\hat{B}_e$, which was more convenient to use for this comparison as follows,

$$\hat{B}_e = \frac{B_e}{\rho \nabla Beam^2} \sqrt{\frac{Beam}{2g}}, \tag{11}$$

where ρ, ∇ and *Beam* stand for fluid density, displacement volume, and breadth of a ship, respectively. For the roll decay tests at SSPA, i.e. the database used in this study, the initial roll angle is normally set to 10 degrees, so that the model test data contain amplitudes in the range from 0 to 10 degrees. The root mean squared error of the equivalent roll damping, $RMSE_{\hat{B}_e}$, for various initial roll angles $\hat{B}_e(\phi_a)$ between estimations using the SI-method and the model test results is,

$$RMSE(\hat{B}_e(\phi_a)) = \sqrt{\frac{\sum_{i=1}^{n} (\hat{B}^{SI}_{e,i}(\phi_a) - \hat{B}^{model}_{e,i}(\phi_a))^2}{n}}, \tag{12}$$

where $\hat{B}^{SI}_{e,i}(\phi_a)$ represents the equivalent roll damping by the SI-method for the ith model test with initial roll angle of ϕ_a, while $\hat{B}^{model}_{e,i}(\phi_a)$ represents the damping from the model tests. The results of the RMSE are plotted in the upper plot of Figure 4. Large values of $RMSE(\hat{B}_e)$ indicate very bad agreement between the SI-method and the model test results for roll damping prediction of modern ships. It should be noted that the accuracy decreases for larger amplitudes where the non-linear portion of the SI-method plays a larger role. Furthermore, in order to illustrate the difference of $\hat{B}_e$ prediction between the SI-method and the model tests at SSPA, the three bottom plots of Figure 4 presents the comparison for three roll amplitudes ϕ_a equal to 0, 5, and 10 degrees, respectively. This shows that accuracy differs greatly between the amplitudes, with the highest accuracy at zero roll amplitude, and it raises the question at what roll amplitude should a comparison be conducted? Should the methods be compared at small or large roll amplitudes? In order to avoid this decision, $\hat{B}_e$ is instead calculated for a range of roll amplitudes (1, 2,..10 degrees).

It was found that most of the ships in the roll damping database were outside the limits suitable to be applied in Equation (9). Figure 5(a) shows the SI-method versus all model tests and versus model tests within the limits. The values of non-

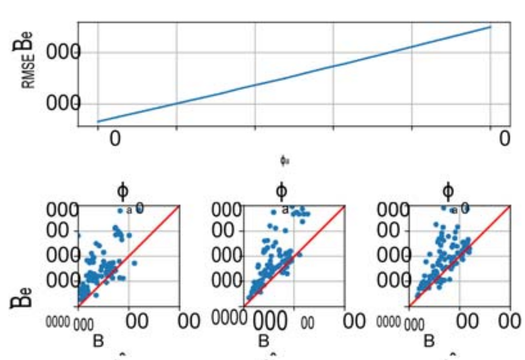

Figure 4. Root mean square error of roll damping prediction between the SI-method and the model test results (upper plot). Influence of roll amplitude ϕ_a on $\hat{B}_e$ between the SI-method and model tests for 0° (bottom left plot), 5° (bottom middle plot) and 10° (bottom right plot), respectively. (This figure is available in colour online.)

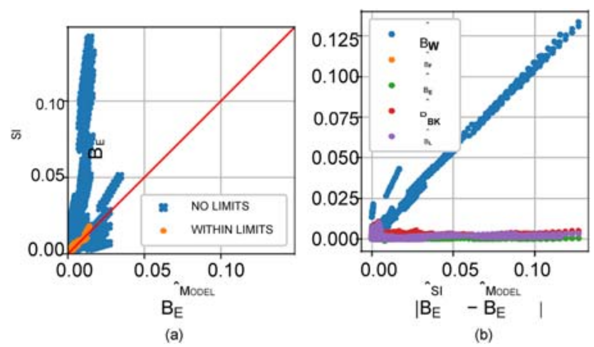

Figure 5. SI-method with and outside limits vs. model tests. (a) Equivalent linearised damping and (b) Residual vs. components. (This figure is available in colour online.)

dimensional equivalent linear damping B_e for roll amplitudes in the range 0 to 10 degrees are displayed. The points within the limits seem to agree much better with the model tests than the points outside the limits (which are far away from the red reference line). Corresponding R^2 are shown in Table 1. The damping components are plotted against the error in Figure 5(b), where it looks like the wave damping B_W is very large when the error is large.

3.2. Sensitivity analysis of the SI-method for all database ships

Since a very large discrepancy between the model test results and the SI-method outside its limits was observed, a sensitivity study was carried out. A so-called 'reference ship' with ship parameters located in the middle of the SI-method applicable boundaries as in Equation (9) is used for the investigation. For the sensitivity study, only the relatively important ship parameters, i.e. C_b,$\frac{Beam}{T}$, $\frac{\overline{OG}}{T}$, A_0, $\frac{BK_B}{Beam}$, $\frac{BK_L}{L_{pp}}$, are chosen to investigate the effects of their variation on different roll damping components. The results of the sensitivity analysis are presented in Figure 6. It can be seen that the wave damping component B_W increases a great deal with the absolute value of $\overline{OG}/T$. It can also be seen that wave damping shows an enormous increase when the beam-to-draught ratio exceeds the input boundary, which seems to be the case for at least one-third of the roll decay tests. It can also be noted that most of the ships in the database have midsection coefficients A_0 and bilge keel heights outside the limits. The unrealistic prediction of wave damping component B_W in terms of $\frac{Beam}{T}$ and $\frac{\overline{OG}}{T}$ should be further examined. If this originates from the original Ikeda's method or is an extrapolation error from the polynomials in SI-method will be examined in the next section.

3.3. Simplified and original Ikeda method

Comparing the results from the SI-method from corresponding results with the original Ikeda's method can be a way to see whether the observed deviations are result from extrapolation or inherent in the original method. In Ikeda's method, more detailed information about the ship hull geometry is needed so that B_W can be calculated with a strip method and B_E can be calculated using sectional Lewis coefficients. It was possible

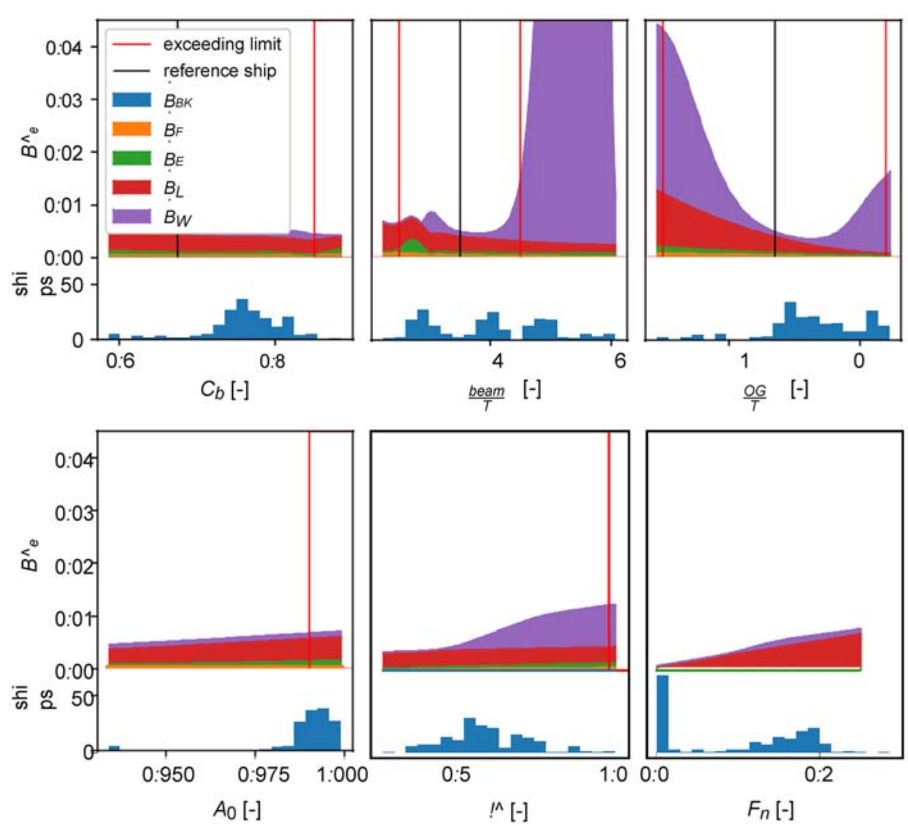

Figure 6. SI-method input parameter variation and data base ships. (This figure is available in colour online.)

Table 1. Validation of SI within and outside limits.

	R^2	Number of points
SI no limits	−46.35	1470
SI within limits	0.83	120

Table 2. Validation of SI and Ikeda.

	R^2	Number of points
Ikeda	0.84	500
SI no limits	−127.95	500

to collect the required hull inputs for 15 ships in the database. These ships were used in 50 of the reference roll decay tests: all but one of the tests exceed the limits. Ikeda's method has a much better agreement for these exceeding model tests according to Figure 7 and the calculated R^2 in Table 2.

4. Regression method based on SSPA database

In order to improve the accuracy of the roll damping prediction, the SSPA database containing more than 250 roll decay tests with modern ships is used to propose new models. In the following, two different approaches are used to build such a model for roll damping prediction. The model is assumed to be a function of the same input parameters as the SI-method. It was found in Section 3.2 that the B_e coefficient changes a great deal with the roll amplitude ϕ_a which introduces a challenge to this regression. Three different options through which to approach this were considered:

- Calculate B_e for only one representative value of ϕ_a.
- Split the problem into two regressions, one for B_1 and one for B_2.
- Calculate B_e for a range of ϕ_a and include all in the regression.

The first option was rejected because that would generate a model that works for one roll amplitude only. The second option was rejected because introducing two regression models was considered unnecessarily complex; it was also suspected that there could be correlations between B_1 and B_2 so that the two regressions needed to be connected in some way. So, the third option was used, which means that the B_e used in the regression contains roll amplitudes from 0 to 10 degrees.

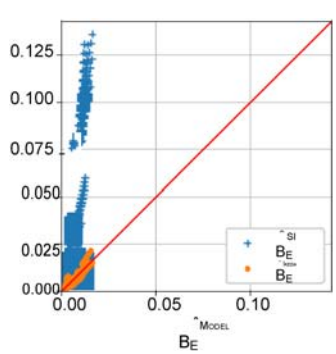

Figure 7. Comparison of SI, Ikeda and model tests. (This figure is available in colour online.)

4.1. Correction of the simplified Ikeda's method

The first approach uses the SI-method as is, but then applies some corrections to the output damping components. A roll amplitude correction factor was also added. The correction factors were determined by fitting a linear regression model to the roll damping components, giving the following expression:

$$\hat{B}_e = 1.106\hat{B}_{BK} - 0.9124\hat{B}_E + 4.282\hat{B}_F + 0.7457\hat{B}_L + 0.1844\hat{B}_W + 0.004999\phi_a - 0.0005097 \tag{13}$$

4.2. New regression model for roll damping

An alternative approach assumes that the function can be expressed as a second-order polynomial. Some statistical learning method is used to establish the regression model. The input parameters (the features) are first transformed into polynomial features including all possible coupling terms. The best polynomial features are selected using a feature selection algorithm and selecting the 'k-best' features with a linear model for testing the individual effect of each feature.

The cross-validation method as described in Section 4.3 is used to estimate accuracy. The optimum number of polynomial features was determined by finding the 'k-value' with the highest accuracy in the cross-validation. A regression model with 12 polynomial features was found to have the best accuracy when evaluated in this way. The model was determined by fitting the selected regression model to the entire data, giving the following expression:

$$\begin{aligned}\hat{B}_e = &-0.02578 A_0 V - 0.02705 BK_B V \\ &+ 0.008993 BK_L V - 0.03191 C_b V - 0.2028 OGV \\ &+ 0.003472 V^2 \\ &+ 0.004234 V\hat{\omega}_0 - 0.002591 V\phi_a - 0.008384 V beam \\ &+ 0.05048 V \\ &+ 0.007814 \hat{\omega}_0{}^2 \\ &+ 0.03882 \hat{\omega}_0 \phi_a - 0.00106914\end{aligned}$$

All the inputs with length scale (T, OG, BK_B, BK_L, $Beam$) are non-dimensionalised with L_{pp}. V is non-dimensionalised using $\sqrt{L_{pp}}$. The midsection coefficients A_0 and block coefficients C_b are non-dimensional. The roll amplitude ϕ_a is in radians.

Table 3. Statistics from cross-validations with all models.

Model	$E[R^2]$	$std(R^2)$
Simplified Ikeda corrected	0.75	0.16
New regression	0.77	0.09

4.3. Cross-validation

When constructing a regression model from a data set, overfitting the data can be a problem. Including too many parameters and/or allowing too high order of the model would give a very good representation of the present roll damping data, but this would produce large extrapolation errors when the model is used on other data. K-fold cross-validation has been used to 'mimic' this situation. The data has been split into five smaller sets (folds). Four of the folds are used to train the model and the fifth is used for testing (validation). The validation is done by calculating the coefficient of determination R^2 for the fitted model. This is done for all five possible train-test combinations. The folds are constructed in a random way with the restriction that all data for a particular ship should be in the same fold. Five folds are generated 20 times randomly, giving 100 values of R^2 from the train-test-procedure for each model. The mean values and standard deviation of these 100 values of R^2 are shown in Table 3. The mean and standard deviation of R^2 for the SI-method in this table was calculated directly instead of using cross-validation, since it does not rely on the SSPA data.

5. Conclusions

A large experimental test database from SSPA including about 250 existing roll decay model tests is used in this study to improve current semi-empirical methods for roll damping prediction. First, the parameter identification technique was used to extract roll damping coefficients from these tests. The method was found to work very well in identifying the parameters in the linear, quadratic and cubic mathematical models, while a quadratic damping model is sufficient to reproduce most of the roll decay tests. It is demonstrated that predictions using the simplified Ikeda's method (SI-method) showed poor agreement with model tests outside its limits but acceptable agreement for the ships within limits. The wave-damping component B_W seemed to be the main source of the error. The ships in the database are recognised as being representative of modern merchant ships that have been tested at SSPA during the past 15 years, including, for instance oil tankers, LNG-tankers, passenger ships, car carriers, and others. That so many of these ships exceed the limits, with expected poor results from the SI-method, is a bit worrying. Furthermore, the original Ikeda method using strip theory based hydrodynamic analysis was also implemented and was found to agree much better with the model tests, also outside the limits of the SI-method. It can therefore be concluded that the wave damping error is caused by extrapolation rather than by errors in the original Ikeda method.

To predict roll damping for modern hull shapes beyond the limits of the present SI-method, two approaches were investigated as to how the SI-method could be used anyway, outside its limitations and based on the SSPA model test database. First, some correction factors were proposed to the five damping components in the SI-method using regression. Second, a completely new method was developed using regression on the test database. The accuracy of these methods were cross validated with significantly improved accuracy. The proposed corrections seem to improve the accuracy of the SI-method for modern ships outside the limits. The new regression model has the highest accuracy, but it is still lower than the SI-method within its limits or the original Ikeda method. Further research efforts should be devoted to creating an updated version of the SI-method. While waiting for a better method to be developed, simplified Ikeda can be extended for modern ships using the new regression or the correction factors proposed in this paper.

Acknowledgments

The authors would like to acknowledge Trafikverket (Swedish Transport Administration) and Lighthouse, swedish maritime competence centre (www.lighthouse.nu) for providing the resources to prepare this paper and also thank all personnel at SSPA that have been involved in the creation of the model test results: building the ship models and conducting the experiments. Also special thanks to Sune Thorsson who collected the meta data about the tested ship models.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Lighthouse [FP4_2020] and Trafikverket.

ORCID

Martin Alexandersson http://orcid.org/0000-0002-9360-078X
Wengang Mao http://orcid.org/0000-0002-7126-1254
Jonas W. Ringsberg http://orcid.org/0000-0001-6950-1864

References

Alexandersson M. 2020. https://github.com/martinlarsalbert/rolldecay-estimators. original-date: 2020-01-31T12:29:37Z.

Bulian G, Francescutto A. 2004. A simplified modular approach for the prediction of the roll motion due to the combined action of wind and waves. Proc Inst Mech Eng Part M J Eng Maritime Environ. 218 (3):189–212.

France WN, Levadou M, Treakle TW, Paulling JR, Michel RK, Moore C. 2001. An investigation of head-sea parametric rolling and its influence on container lashing systems. Page 24.

Froude W. 1861. On the rolling of ships. The Royal Institution of Naval Architects (RINA), UK, Transactions of the Institution of Naval Architects. Vol. 2; p. 180–227.

Galeazzi R, Blanke M, Poulsen NK. 2013. Early detection of parametric roll resonance on container ships. IEEE Trans Control Syst Technol. 21(2):489–503.

Himeno Y. 1981. Prediction of ship roll damping – state of the art. University of Michigan Department of Naval Architecture and Marine Engineering. Report no: 239.

Ikeda Y. 1978a. On eddy making component of roll damping force on naked hull. University of Osaka Prefacture, Department of Naval Architecture, Japan, Report No. 00403, Published in: Journal of Society of Naval Architects of Japan, Volume 142. [accessed 2020 January 27]. https://repository.tudelft.nl/islandora/object/uuid%3A09d79a4d-cd3d-423f-9b23-43a311096202.

Ikeda Y. 1978b. On roll damping force of ship – effect of friction of hull and normal force of bilge keels. University of Osaka Prefecture, Department of Naval Architecture, Japan, Report No. 00401, Published in: Journal of Society of Naval Architects of Japan, No.

161 (1976) [accessed 2020 May 14]. https://repository.tudelft.nl/islandora/object/uuid%3A49ab141b-b5f2-4d29-84ae-e6aa1948c729.

Ikeda Y. 1979a. On roll damping force of ship -- effect of hull surface pressure created by bilge keels. University of Osaka Prefacture, Department of Naval Architecture, Japan, Report No. 00402, Published in: Journal of Society of Naval Architects of Japan, No. 165, 1979 [accessed 2020 March 4]. https://repository.tudelft.nl/islandora/object/uuid%3A7c9eac1c-4225-4d5c-89c1-04066c30c0de.

Ikeda Y. 1979b. Velocity field around ship hull in roll motion. University of Osaka Prefacture, Department of Naval Architecture, Japan, Report No. 00406, Published in: Journal of Society of Naval Architects of Japan, No. 171, 1978. [accessed 2020 May 14]. https://repository.tudelft.nl/islandora/object/uuid%3Ac20c11e0-0df3-4c76-84bb-0f24ab0e517f.

Ikeda Y, Himeno Y, Tanaka N. 1978. Components of roll damping of ship at forward speed. J Soc Naval Arc Jpn. 1978(143):113–125.

IMO. 2006. 1200 – interim guidelines for alternative assessment of the weather criterion – Netherlands Regulatory Framework (NeRF) – Maritime.

IMO. 2016. Finalization of second generation intact stability criteria draft consolidated explanatory notes for the second generation intact stability criteria. Submitted by the United States.

ITTC. 2011. ITTC – Recommended procedures numerical estimation of roll damping.

Kawahara Y, Maekawa K, Ikeda Y. 2011. A simple prediction formula of roll damping of conventional cargo ships on the basis of Ikeda's method and its limitation. In: Almeida Santos Neves M, Belenky VL, de Kat JO, Spyrou K, and Umeda N, editors. Contemporary ideas on ship stability and capsizing in waves, Fluid Mechanics and Its Applications, Dordrecht: Springer Netherlands; p. 465–486.

Kristiansen T, Ruth E, Firoozkoohi R, Borgen H, Berge B. 2014. Experimental and numerical investigation of ship roll damping with and without bilge keels. Vol. 1B.

Piehl HP. 2016. Ship roll damping analysis.

Rudakovié S. 2017. On application of standard methods for roll damping prediction to inland vessels. p. 9.

Söder C-J, Rosén A, Huss M. 2019a. Ikeda revisited. J Marine Sci Technol. 24(1):306–316.

Söder C-J, Rosén A, Werner S, Huss M, Kuttenkeuler J. 2019b. Assessment of ship roll damping through full scale and model scale experiments and semi-empirical methods. In: Belenky VL, Spyrou KJ, van Walree F, Almeida Santos Neves M, and Umeda N, editors. Contemporary Ideas on Ship Stability: Risk of Capsizing, Fluid Mechanics and Its Applications. Cham: Springer International Publishing; p. 177–190.