

# Experimental Study on Extinction Curve Fitting Expressions of Ship Roll Damping

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(Received: 2 February 2026 / Revised: 6 February 2026 / Accepted: 11 February 2026 / Available Online: 7 March 2026)

**Abstract**—Roll damping plays a crucial role in the accurate prediction of ship roll motion. In potential flow theory, viscous roll damping is not inherently accounted for and therefore must be introduced through experimental model test results. Free roll decay tests are commonly conducted to determine roll damping characteristics, including both linear and nonlinear damping (quadratic) components. In experimental practice, roll damping coefficients obtained from roll decay tests are often expressed using different mathematical formulations curve fitting, such as linear, quadratic, and Bertin's equations. Objective of this study is to evaluate the effect of extinction curve fitting expressions with consider peak to peak and trough to trough extrema value from roll decay test datas. In this study, free roll decay tests were performed on three ship models, and the resulting roll decay responses were analyzed using the three damping expressions for curve extinctions of measured data. The linear and quadratic roll damping coefficients were extracted for each model and formulation. The results indicate that the selected extinction curve expression and fitting method significantly influence the estimated roll damping coefficients. In addition, the choice of using peak-to-peak or trough-to-trough data in the roll decay analysis was found to affect the obtained damping values. Based on the comparative analysis, it is concluded that averaging the damping coefficients derived from both peak-based and trough-based fitting provides a more representative estimation of roll damping for the tested ship models.

**Keywords**—free roll decay test, roll damping, linear equation, quadratic equation, bertin's equation

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## I. INTRODUCTION

Roll motion is a critical aspect of ship dynamics due to its significant influence on vessel safety, operability, and seakeeping performance. Excessive roll responses can compromise cargo safety, reduce operational limits, and increase the risk of capsizing. An accurate characterization of roll damping is therefore essential in both ship design and performance assessment, particularly in the context of stability and motion prediction. For engineering purposes, the roll motion of a floating structure can be predicted more or less reliably using semi-empirical and empirical methods [1].

Roll damping encompasses various energy dissipation mechanisms, including viscous effects, wave radiation, flow separation, vortex shedding, and the

action of appendages such as bilge keels. Owing to the complex and highly nonlinear nature of these phenomena, roll damping cannot be determined reliably from theoretical considerations alone and is commonly evaluated through experimental techniques. Among these, the roll decay test remains one of the most widely adopted methods for estimating roll damping characteristics of ship models.

In the analysis of roll decay tests, the damping moment is frequently expressed using simplified mathematical representations. Linear roll damping models, in which the damping moment is assumed proportional to the roll velocity, are often applied for small-amplitude roll motions. For roll motions of a small amplitude, a linear formulation can provide more or less reliable predictions [2][3]. However, as the roll amplitude increases, nonlinear viscous effects become increasingly significant. To account for these effects, non-linear roll damping models should be considered. Consequently, combined linear and non-linear damping formulations are extensively employed to represent roll decay behavior and to extract roll damping coefficients from experimental data. The nonlinear contribution can result from the nonlinearity of the restoring component or the nonlinearity of the damping component [4]. Free roll decay test is the most widely used method [5-9] because it is the recommended technique by the International Maritime Organization (IMO) [10]. Roll damping modelling expression from roll decay test was already discussed by Froude [11][12] and since his early contribution this topic has remained in the focus of several researchers. The mathematical representation of roll damping and the analysis of related experimental data have been central topics in numerous studies. [13-15]. The coefficient obtained from the roll decay test is often used to describe the roll motion damping

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capability. Where is the coefficients are commonly expressed using different mathematical formulations, such as linear, quadratic, or Bertin-type equations. In the study [16] that has been conducted regarding the comparison of four estimation methods for determining the roll damping ratio using a series of free roll decay tests with linear expression, [17] expressed the results of roll decay on several small crafts in Bertin's coefficient, [18] study on roll damping describes the results of the roll decay test in the form of a quadratic equation. Meanwhile [19] presents the results of roll decay in the form of a quadratic expression and the form of the Bertin coefficient without discussing the comparison of the two forms of expression.

In many previous studies, the roll decay data processing procedures are not explicitly described, particularly with respect to whether peak-to-peak or trough-to-trough extrema data and kind of curve fitting expressions are used in the damping identification. As a result, the influence of extrema selection and trendline of fitting expression on the estimated roll damping coefficients is often not clearly described. Moreover, limited attention has been given to the effect of different

extinction curve fitting expressions on the magnitude and distribution of linear and nonlinear damping components. This lack of specificity complicates direct comparison between studies and motivates a more systematic examination of data selection and fitting formulation in roll decay analysis.

Therefore, objective of this study is to evaluate the effect of extinction curve fitting expressions: linear, quadratic, and Bertin's equations on the estimation of roll damping coefficients. Particular attention is given to the influence of data extraction from peak to peak and trough to trough roll decay test data of ship model experiments, in order to clarify their impact on the resulting damping characteristics.

## II. METHOD

### A. Model Test

The roll decay test was conducted to determine the roll damping characteristics of the ship model through free roll motion. The experiments were carried out in a Maneuvering Ocean Basin at Hydrodynamic Laboratory – BRIN, with basin dimensions 60 meters (length) × 35 meters (width) × 2.5 meters (depth).



Figure 1. LCT ship model-Model-1



Figure 2. Ferry ship model-Model-2



Figure 3. Container ship model-Model-3

TABLE 1  
 PRINCIPAL DIMENSIONS

Item	Dimensions		
	Model-1	Model-2	Model-3
Length between perpendiculars, $L_{pp}$ (m)	2.50	3.00	2.93
Breadth, $B$ (m)	0.63	0.71	0.50
Draught, $d$ (m)	0.13	0.15	0.08
Displacement, $\Delta$ (kg)	157.12	203.57	94.5
$LCG/L_{pp}$	0.50	0.46	0.48
$KG/d$	1.90	1.94	1.31
$GM/d$	0.94	1.03	2.79
$k_{xx}/B$	0.32	0.34	0.31
Scale	19.83	19.08	62

The roll decay experiments were conducted using three scaled ship models : LCU, Ferry and Container ship model were named Model-1, Model-2 and Model-3 as shown at **Figure2 1-3** respectively. The principal dimensions of the model, defining its geometric and hydrostatic properties, are presented in **Table 1**. The model was built according to Froude. The model was set to the target loading condition and carefully ballasted to ensure correct mass distribution properties.

The roll motion of the model was measured using an optical motion tracking system manufactured by Qualisys. Reflective markers were rigidly mounted on the ship model at predefined locations to ensure accurate detection of the model motion. The motion tracking system recorded the three-dimensional positions of the markers, from which the six degrees of freedom (6-DOF) motions of the model (surge, sway, heave, roll, pitch, and yaw ) were obtained. The roll angle time histories were extracted from the reconstructed 6-DOF motion data and used for further analysis. Prior to the roll decay test for measurement accuracy all instrumentation devices have been calibrated previously.

The experiment was performed in calm water conditions to eliminate the influence of waves and external disturbances. During the roll decay test, the model was initially inclined to a prescribed heel angle by applying a slow and steady manual force on one side of the hull. The heeling motion was performed gradually in order to avoid inducing significant translational motions or other rotational modes. Once the desired initial roll

angle was reached, the external force was suddenly released, allowing the model to undergo free roll oscillations about its equilibrium position.

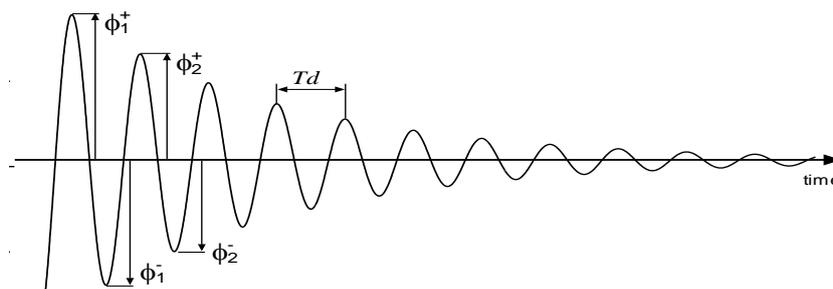
#### B. Estimation of Linear and Quadratic Roll Damping Coefficients

The roll motion of the ship model during a roll decay test can be described by the linearized roll equation of motion with nonlinear damping terms:

$$(I_{\phi} + I_{\phi}')\ddot{\phi} + b_1\dot{\phi} + b_2\phi'|\phi'| + C_{\phi}\phi = 0 \quad (1)$$

where  $(I_{\phi} + I_{\phi}')$  is the roll moment of inertia including added inertia,  $C_{\phi}$  is the linear restoring coefficient, and  $b_1$  and  $b_2$  denote the linear and quadratic roll damping coefficients, respectively. For roll motion, viscous effect is significant and the decay behavior is commonly represented using combined linear and quadratic damping.

The roll decay response is characterized by a sequence of alternating peaks and troughs in the roll angle time history. Let  $\phi_n$  and  $\phi_{n+1}$  denote two successive extrema (peak to peak or trough to trough), separated by the damped roll period  $T_d$ . The peak to peak (or trough to trough) method calculated the roll natural period by averaging the periods. The consecutive roll amplitude  $\phi_1^+$ ,  $\phi_2^+$ , ... for peak to peak and  $\phi_1^-$ ,  $\phi_2^-$ , ... for trough to trough are defined as **Figure 4**.



**Figure 4.** Time traces of roll decay

If equation (1) divided by  $(I_{\phi} + I_{\phi}')$  then get :

$$\phi'' + 2\alpha\phi' + \beta\phi + \omega^2\phi = 0 \quad (2)$$

with assumed  $b_1/(I_{\phi} + I_{\phi}') = 2\alpha$ ,  $b_2/(I_{\phi} + I_{\phi}') = \beta$  and  $\omega^2 = C_{\phi}/(I_{\phi} + I_{\phi}')$

The energy dissipated in motion decay for each roll period is the integral of equation (2) .

$$\int_0^T \phi'' \frac{d\phi}{dt} dt + \int_0^T 2\alpha\phi' \frac{d\phi}{dt} dt + \int_0^T \beta\phi \frac{d\phi}{dt} dt + \int_0^T \omega^2\phi \frac{d\phi}{dt} dt = 0 \quad (3)$$

if roll oscillation is assumed :

$$\phi = \phi_o \cos(\omega t) \quad (4)$$

then

$$\int_0^T \phi'' \frac{d\phi}{dt} dt = 0 \quad (5)$$

$$\int_0^T 2\alpha\phi' \frac{d\phi}{dt} dt = \alpha\phi_o^2\omega^2 T_d \quad (6)$$

$$\int_0^T \beta\phi \frac{d\phi}{dt} dt = \frac{8}{3}\beta\phi_o^3\omega^2 \quad (7)$$

$$\int_0^T \omega^2\phi \frac{d\phi}{dt} dt = \int_{\phi_n}^{\phi_{n+1}} \omega^2\phi d\phi = \frac{\omega^2}{2}(\phi_{n+1} + \phi_n)(\phi_{n+1} - \phi_n) = -\omega^2\phi_o\Delta\phi \quad (8)$$

where  $\Delta\phi = (\phi_n - \phi_{n+1})$  and  $\phi_o = (\phi_{n+1} + \phi_n)/2$   
then the summation result of equations (5),(6),(7) and (8) is obtained :

$$\alpha\phi_o^2\omega^2 T_d + \frac{8}{3}\beta\phi_o^3\omega^2 = \omega^2\phi_o\Delta\phi \quad (9)$$

then divided by  $\phi_o^2\omega^2$  will be obtained :

$$\alpha T_d + \frac{8}{3}\beta\phi_o = \frac{\Delta\phi}{\phi_o} \quad (10)$$

if  $p = \alpha T_d$  and  $q = 8/3.\beta$  the (10) can be described as linear equation (Method-A):

$$p + q\phi_o = \frac{\Delta\phi}{\phi_o} \quad (11)$$

with same way if the equation (9) is divided by  $\phi_o\omega^2$  will be obtained :

$$\alpha T_d\phi_o + \frac{8}{3}\beta\phi_o^2 = \Delta\phi \quad (12)$$

then the (12) can be described as quadratic equation (Method-B) :

$$p\phi_o + q\phi_o^2 = \Delta\phi \quad (13)$$

if the (9) is divided by  $\phi_o^3\omega^2$  will be obtained:

$$\frac{\alpha T_d}{\phi_o} + \frac{8}{3}\beta = \Delta\phi / \phi_o^2 \quad (14)$$

the expression equation (14) similarly describe in [20] the decrement in roll amplitude per period  $\Delta\phi$  is defined as the square function of the average amplitude  $\phi_o^2$  and presented as the Bertin's equation as follows:

$$N = \Delta\phi / \phi_o^2 \quad (15)$$

then the equation (14) can be expressed as (Method-C):

$$\frac{p}{\phi_o} + q = N \quad (16)$$

The roll decay time history data were subsequently processed to determine the linear and quadratic roll damping coefficients,  $p$  and  $q$ , using three different extinction curve formulations. Method-A corresponds to a linear extinction expression, Method-B represents a quadratic extinction formulation, and Method-C applies the Bertin extinction equation. The  $p$  and  $q$  values can be determined using least square fitting method from the extinction curves approach of the decay data derived from successive peaks and troughs for each expression equation, furthermore linear roll damping coefficient  $b_1$  and quadratic roll damping coefficient  $b_2$  can be obtained as follows :

$$b_1 = 2(I_{\phi} + I_{\phi}')p / T_d \quad (17)$$

$$b_2 = 3/8(I_{\phi} + I_{\phi}')q \quad (18)$$

to get the values of  $b_1$  and  $b_2$ , the added roll inertia value is also needed, where the roll moment of inertia  $(I_{\phi} + I_{\phi}')$  is the sum of the roll inertia of ship  $I_{\phi} = \Delta k_{xx}^2$  and the added roll inertia  $I_{\phi}'$ . The roll natural frequency  $\omega_d = 2\pi/T_d = \sqrt{C_{\phi}/(I_{\phi} + I_{\phi}')}$ , with the roll restoring coefficient  $C_{\phi} = \Delta GM$ , where  $\Delta$  is ship displacement,  $k_{xx}$  is roll radius gyration and  $GM$  is the ship transversal metacentric height, so that the added roll inertia can be determined  $I_{\phi}' = (C_{\phi}/\omega_d^2) - I_{\phi}$ .

### III. RESULTS AND DISCUSSION

The time histories of the free roll decay tests obtained from the experiments are presented for Models 1, 2, and 3 in **Figures 1-3** respectively. These time traces illustrate the decay characteristics of the roll motion under calm water conditions. The measurement of the roll natural period is important, not only for identifying the roll natural period of the ship model, but also as a

key parameter in the calculation of roll damping coefficients.

TABLE 2  
 MEASURED RESULTS OF ROLL NATURAL PERIOD

	$T_d$ (sec.)		
	Model-1	Model-2	Model-3
peak to peak	5.9851	5.9753	7.2012
trough to trough	5.9851	5.9754	7.2012
average	5.9851	5.9754	7.2012

Subsequently, the roll decay time history data were processed to determine the linear and quadratic roll damping coefficients,  $p$  and  $q$ . The coefficients were estimated using Methods A, B, and C for each ship model respectively, the corresponding extinction curves for the three methods are presented in **Figures 4–12**, illustrating the damping characteristics and the influence of the selected formulation on the extracted roll damping coefficients.

The measured roll natural periods for Models-1, 2, and 3 are summarized in **Table 2**. The natural period was determined based on the average values obtained from peak-to-peak and trough-to-trough roll periods each cycle. The measured average value represents the mean of the peak-based and trough-based periods, where average value  $T_d$  for Model-1 : 5.9851 sec., Model-2 : 5.9754 sec., and Model-3 : 7.2012 sec.

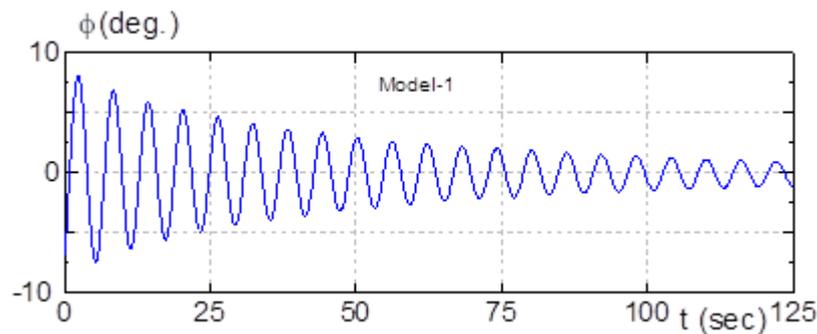


Figure 5. The measured time histories of roll decay test Model-1

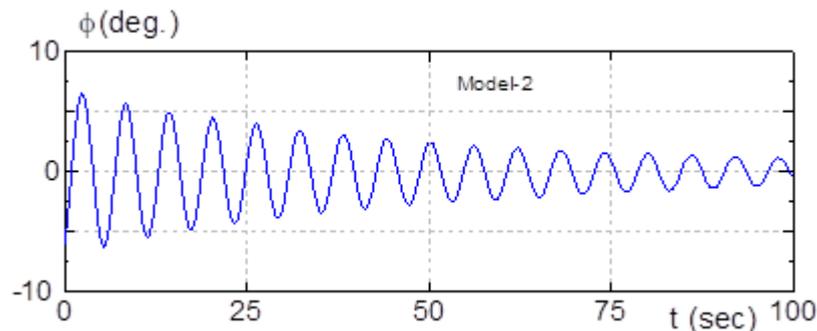


Figure 6. The measured time histories of roll decay test Model-2

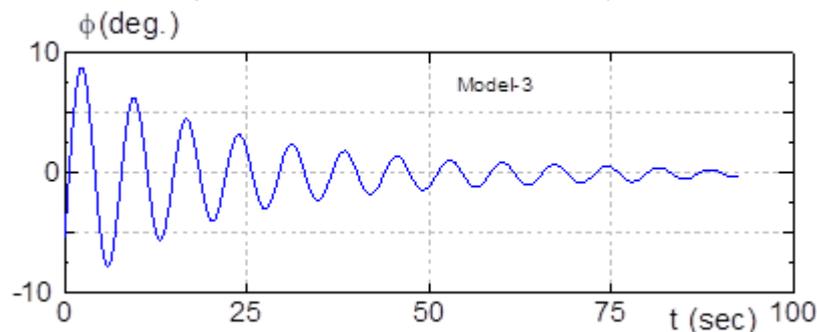


Figure 7. The measured time histories of roll decay test Model-3

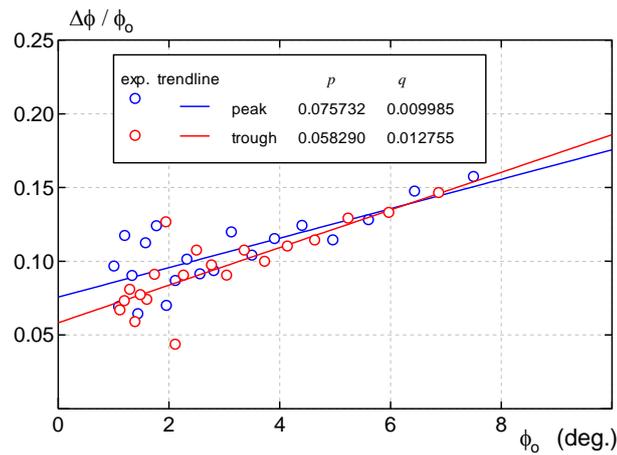


Figure 8. Curve of extinction with Method A for ship Model-1

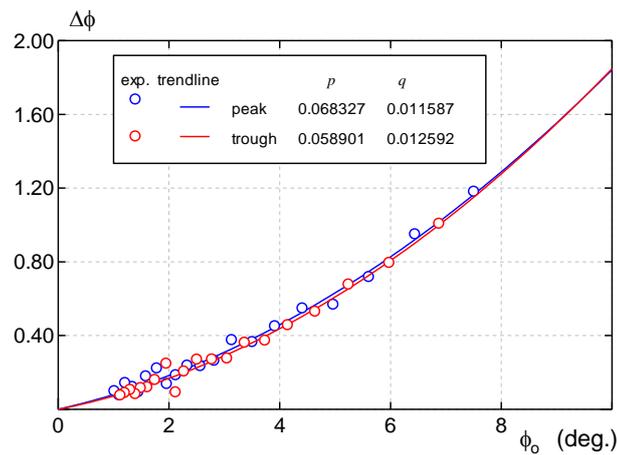


Figure 9. Curve of extinction with Method B for ship Model-1

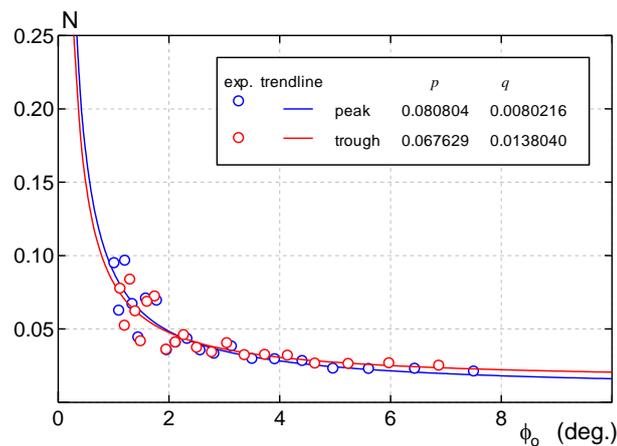


Figure 10. Curve of extinction with Method C for ship Model-1

TABLE 3  
 MEASURED RESULTS OF ROLL DAMPING COEFFICIENTS  
 MODEL-1

	Method-A		Method-B		Method-C	
	<i>p</i>	<i>q</i>	<i>p</i>	<i>q</i>	<i>p</i>	<i>q</i>
peak to peak	0.075732	0.009985	0.068327	0.011587	0.080804	0.008022
trough to trough	0.058290	0.012755	0.058901	0.012592	0.067629	0.013804
average	0.067011	0.011370	0.063614	0.012089	0.074217	0.010913

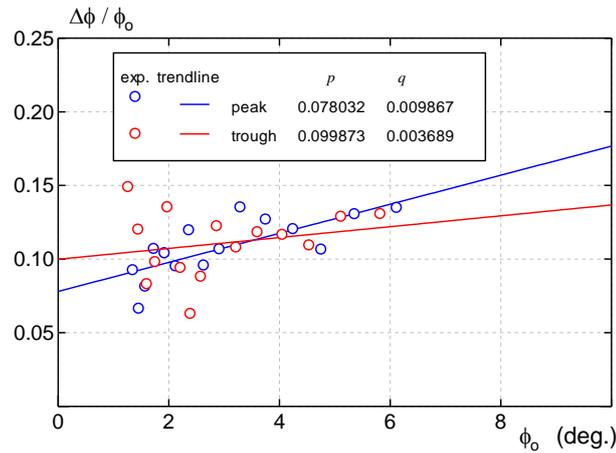


Figure 11. Curve of extinction with Method A for ship Model-2

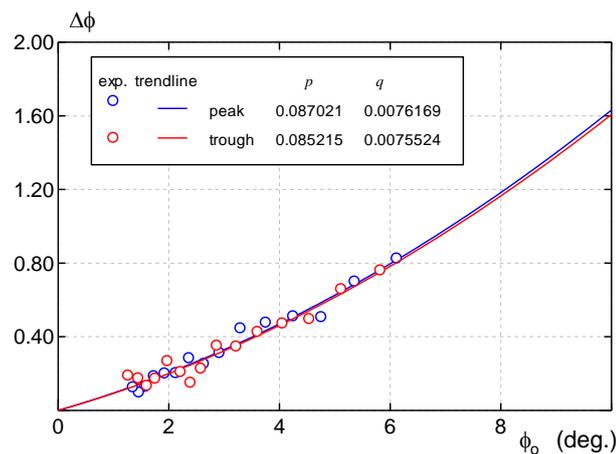


Figure 12. Curve of extinction with Method B for ship Model-2

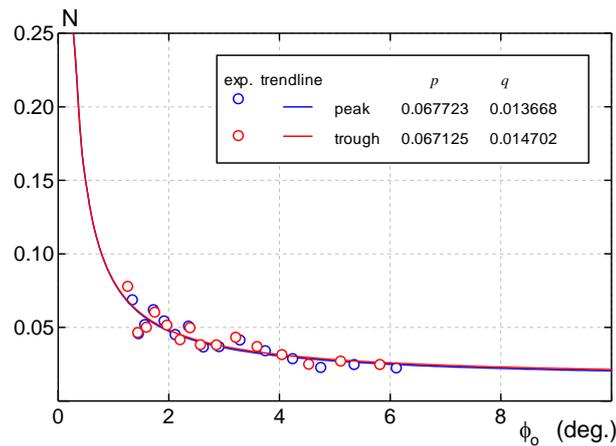


Figure 13. Curve of extinction with Method C for ship Model-2

TABLE 4  
 MEASURED RESULTS OF ROLL DAMPING COEFFICIENTS  
 MODEL-2

	Method-A		Method-B		Method-C	
	<i>p</i>	<i>q</i>	<i>p</i>	<i>q</i>	<i>p</i>	<i>q</i>
peak to peak	0.078032	0.009867	0.087021	0.007617	0.067723	0.013668
trough to trough	0.099873	0.003690	0.085215	0.007552	0.067125	0.014702
average	0.088952	0.006778	0.086118	0.007585	0.067424	0.014185

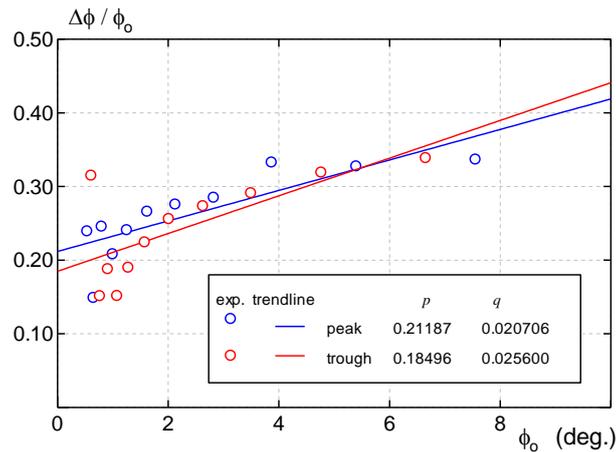


Figure 14. Curve of extinction with Method A for ship Model-3

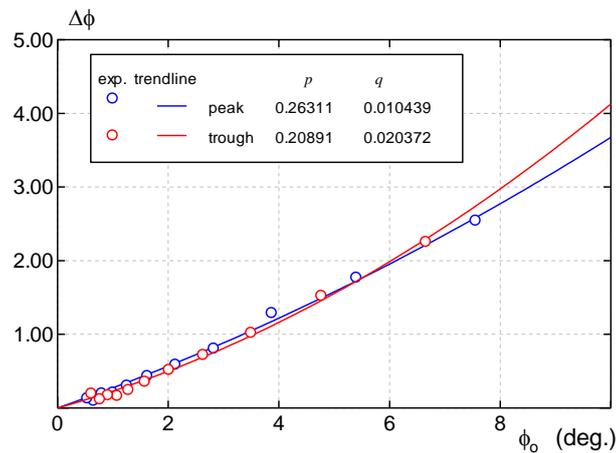


Figure 15. Curve of extinction with Method B for ship Model-3

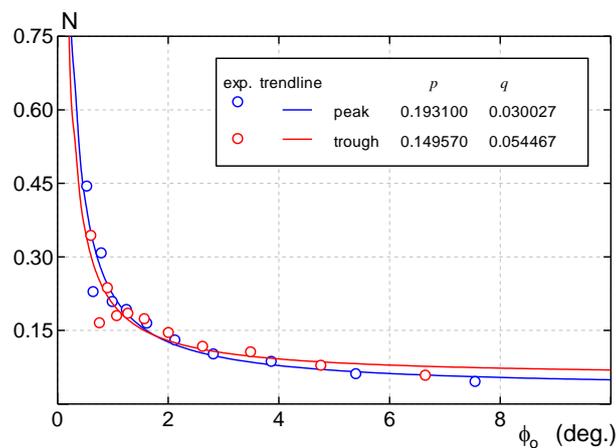


Figure 16. Curve of extinction with Method C for ship Model-3

TABLE 5  
 MEASURED RESULTS OF ROLL DAMPING COEFFICIENTS  
 MODEL-3

	Method-A		Method-B		Method-C	
	<i>p</i>	<i>q</i>	<i>p</i>	<i>q</i>	<i>p</i>	<i>q</i>
peak to peak	0.21187	0.020706	0.26311	0.010439	0.19310	0.030027
trough to trough	0.18496	0.025600	0.20891	0.020372	0.14957	0.054467
average	0.19841	0.023153	0.23601	0.015406	0.17134	0.042247

The measured results of roll period indicate that no significant differences are observed between the peak-to-peak and trough-to-trough natural periods for all ship models considered in this study. This consistency suggests that the roll motion during the decay tests is symmetric and that the period estimation is not sensitive in the analysis effect of peak to peak or trough to trough.

The roll damping expressions that have been obtained for Model-1 using the linear, quadratic, and Bertin formulations are presented in **Figures 8–10**, respectively. The results indicate that the values of the linear damping coefficient  $p$  are consistently larger than those of the quadratic damping coefficient  $q$  across all applied methods. This observation suggests that the linear damping component is dominant compared to the nonlinear damping component for this model. A similar trend is observed for Model-2, as shown in **Figures 11–13**, and for Model-3, as presented in **Figures 14–16**. In all cases, the linear damping coefficient exceeds the quadratic damping coefficient, indicating that linear damping plays a more significant role in the roll decay response of the tested models.

The tabulated values of the linear and quadratic roll damping coefficients,  $p$  and  $q$ , together with their corresponding average values for each method, are summarized in **Tables 3–5** for Model-1, 2, and 3, respectively.

Differences between the linear- $p$  and quadratic- $q$  roll damping coefficients derived from peak-to-peak and trough-to-trough data are primarily associated with the nonlinear and asymmetric nature of roll damping mechanisms observed during roll decay tests. First, roll damping is strongly influenced by viscous effects such as flow separation, and vortex shedding. These phenomena are inherently nonlinear and may not be perfectly symmetric between positive and negative roll motions. As a result, the energy dissipation occurring during one half-cycle of roll motion may differ slightly from that of the opposite half-cycle, leading to variations in damping coefficients estimated from peaks and troughs. Second, experimental factors such as minor residual motions in other degrees of freedom, imperfect initial release conditions, or small disturbances in the

free surface may affect one side of the roll motion more than the other. Although these effects are minimized during testing, they can still contribute to small discrepancies between peak-based and trough-based estimates.

The estimation procedures themselves involve fitting decay data over limited segments of the time history. When peak-to-peak and trough-to-trough data are processed separately, the number of data points and their distribution over the roll amplitude range may differ, which can influence the regression results used to extract the damping coefficients, small differences between peak-to-peak and trough-to-trough damping coefficients are expected and do not indicate inconsistency in the experimental results. Then, averaging the coefficients obtained from both extrema is therefore commonly adopted to obtain representative roll damping values.

**Table 6** shown summarizes the linear and quadratic roll damping coefficients,  $b_1$  (linear component) and  $b_2$  (quadratic component), obtained for all ship models using the three extinction curve fitting methods. The coefficients were derived from further processing of the average values of  $ppp$  and  $qqq$  for each method. Although the same roll decay time histories were used, the three methods yield different combinations of  $b_1$  and  $b_2$ . A clear trade-off between the linear and quadratic damping components is observed: methods producing higher values of  $b_1$  generally result in lower values of  $b_2$ , and vice versa. This behavior reflects the different assumptions underlying each extinction curve formulation in representing energy dissipation during roll decay. The linear extinction formulation tends to attribute a larger portion of the decay to linear damping, thereby reducing the contribution assigned to the quadratic term. In contrast, the quadratic and Bertin formulations allow a greater share of the decay to be represented by nonlinear damping, leading to relatively higher  $b_2$  values. Consequently, the damping energy is redistributed between the linear and quadratic components depending on the selected fitting expression, while the overall decay behavior remains consistent with the measured time histories.

TABLE 6  
 MEASURED DAMPING COEFFICIENTS

MODEL-1	$b_1$	$b_2$
<i>Method-A</i>	38,817,000	1,234,900
<i>Method-B</i>	36,849,000	1,313,000
<i>Method-C</i>	42,991,000	1,185,300
MODEL-2	$b_1$	$b_2$
<i>Method-A</i>	51,269,000	732,520
<i>Method-B</i>	49,636,000	819,670
<i>Method-C</i>	38,861,000	1,532,900
MODEL-3	$b_1$	$b_2$
<i>Method-A</i>	166,230,000	3,637,100
<i>Method-B</i>	197,730,000	2,420,100
<i>Method-C</i>	143,550,000	6,636,500

These results indicate that the choice of extinction curve formulation has a significant influence on the identified roll damping coefficients, even when identical experimental data are used. Therefore, careful consideration of the selected damping expression is required when interpreting roll decay test results and when applying the obtained coefficients in roll motion prediction and seakeeping analyses.

#### IV. CONCLUSION

Free roll decay tests were performed on three ship models to examine the influence of extinction curve formulations on the identification of roll damping characteristics. To improve representativeness, the linear and quadratic damping coefficients,  $p$  and  $q$ , obtained from each fitting method were averaged and subsequently used to determine the linear and quadratic roll damping components,  $b_1$  and  $b_2$ . The analysis demonstrates that linear, quadratic, and Bertin expressions yield systematically different combinations of  $b_1$  and  $b_2$ , even when derived from identical roll decay time histories. A consistent trade-off between the linear and nonlinear damping components is observed, indicating that each extinction formulation redistributes the total damping contribution in a distinct manner. This behavior confirms that roll damping coefficients are not unique properties of the experiment alone, but are also strongly dependent on the selected mathematical representation.

These findings highlight the necessity of carefully selecting and clearly stating the extinction curve formulation used in roll decay analysis. For applications in roll motion prediction and seakeeping assessment, the chosen damping expression should be aligned with the intended modeling approach and roll amplitude range. The present study provides experimental evidence supporting the need for methodological consistency when deriving roll damping coefficients from free roll decay tests.

#### ACKNOWLEDGEMENTS

The authors gratefully acknowledge all staffs at Hydrodynamic Laboratory-BRIN, Surabaya for their cooperation and facilities.

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