On application of standard methods for roll damping prediction to inland vessels

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ABSTRACT

Proper estimation of roll damping moment is of paramount importance for adequate assessment of dynamic stability of ships. However, experimental data on roll damping of inland vessels are scarce and unreliable. Thus the applicability of classic Ikeda's method and its simplified version on typical European inland vessels is investigated, with specific focus on eddy making component. It is found that the simplified Ikeda's method, in comparison to the classic method, may considerably underestimate the eddy making component of damping of full hull forms, or even return negative values, although the block coefficient is within the limits of method applicability. Hence, the paper explores possibilities of adjusting the simplified Ikeda's method in order to improve the observed shortcoming, as well as to extend its application to stability analysis of inland ships.

Keywords: *Inland vessels, roll damping, Ikeda's method, simplified Ikeda's method, eddy damping.*

1. INTRODUCTION

Proper mathematical modeling of ship dynamics was indicated by Bačkalov et al (2016) as one of the most important tasks of future research on stability of inland vessels. In this respect, it is well-known that the outcome of the analysis of roll motion and, consequently, assessment of ship stability, considerably depend on roll damping. However, experimental data on roll damping of inland vessels are scarce and unreliable. In such case, a possible solution could be to use some of the existing semi-empirical methods in order to estimate roll damping coefficients.

Nevertheless, the viability of such approach is questionable knowing that the available methods are primarily intended for conventional seagoing ships. This concerns the well-established Ikeda's method (Himeno, 1981) and its "simplified" version (Kawahara et al, 2009) based on regression analysis of data generated by applying the classic method on a series of ships developed from the Taylor series. The question of applicability of the simplified method is particularly relevant as it was recommended for use within the Second Generation Intact Stability Criteria framework (see, e.g. IMO, 2016), in absence of either experimental data or another, more suitable method.

In order to examine the relevance of the classic and simplified Ikeda's method for inland vessels, roll damping coefficients were calculated, using both methods, for several sample ships. The preliminary results were quite unexpected: for some ships, roll damping coefficients estimated by simplified method were found to be negative. Such results triggered further investigation with even more surprising findings that could concern safety assessment of seagoing ships as well. It is therefore believed that the outcome of the present study is not relevant for inland vessels only, but could have an impact on ship stability analysis in general.

2. APPLICATION OF THE METHODS TO SAMPLE INLAND VESSELS

Inland vessel hulls often have high breadth-to-draught ratios (i.e. $B/d > 4$), while geometry of some of the aft cross sections may yield as much as $B/d \approx 10$. In addition, hull form coefficients of these vessels are typically C_B = 0.82 ÷ 0.94 and $C_M \geq$ 0.99. The geometric properties of inland cargo ships used in the present investigation are given in Table 1.

Simplified Ikeda's method

Due to the aforementioned specific features, most of the vessels in Table 1 are clearly out of range of applicability of Ikeda's method. According to Kawahara et al (2009), the simplified method may be applied to ships having:

$$0.5 \leq C_B \leq 0.85\,,\ 2.5 \leq B/d \leq 4.5\,,\ \hat{\omega} \leq 1\,,$$
$$-1.5 \leq OG/d \leq 0.2\,,\ 0.9 \leq C_M \leq 0.99\,.$$

Symbol $\hat{\omega}$ stands for non-dimensional frequency:

$$\hat{\omega} = \omega \cdot \sqrt{\frac{B}{2g}}\,,$$

while the distance OG of the center of gravity from the calm water level from is downwards positive.

Table 1: Sample inland vessels.

Vessel	*L* [m]	*B* [m]	*d* [m]	C_B	*B/d*
T1	66.00	10.50	3.45	0.8212	3.043
T2	84.28	9.56	3.60	0.9226	2.656
T3	81.821	9.40	3.07	0.8497	3.062
T4	85.95	10.95	2.80	0.8535	3.911
T5	85.95	11.40	4.30	0.8514	2.651
T6	105.76	11.40	2.80	0.8806	4.071
C7	110.00	11.45	2.60	0.8783	4.634
C8	109.70	11.40	2.46	0.8664	4.404
C9	111.25	14.50	3.30	0.8336	4.390
T10	121.10	11.40	4.30	0.8976	2.651
T11	125.00	11.40	4.50	0.8992	2.533
C12	134.26	14.50	3.60	0.9031	4.028
C13	135.00	14.50	4.00	0.9123	3.625
C14	135.00	11.45	2.68	0.9088	4.272
C15	135.00	11.45	3.33	0.9101	3.438

Nevertheless, the roll damping coefficients were calculated for all sample ships, whereby the total roll damping was considered to consist of:

$$B_{44} = B_F + B_W + B_E\,, \tag{1}$$

where B_F is friction damping, B_W is wave damping and B_E is eddy damping. Bilge keel damping B_{BK} is omitted from the calculations, since inland vessels normally do not have bilge keels. Lift damping component B_L is also excluded, since it is considered that the vessel speed is v = 0. It should be noted that whenever the limits of applicability range were exceeded, maximal values of *B/d*, C_B and C_M were used in the calculations. Consequently, since the use of the simplified method does not require knowledge of any details of hull geometry that would distinguish an inland vessel from a seagoing one, the calculated B_{44} coefficients could formally correspond to a Taylor standard series ship of the same characteristics.

Fig. 1 shows the non-dimensional equivalent linear total roll damping:

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

as a function of roll amplitude for all ships examined. It can be noticed that, except for the sample vessels T1 and C9, the total roll damping of the examined ships decreases with the increase of roll amplitude. Surprisingly, some ships (T2 and T10) may even reach negative roll damping at large enough rolling amplitudes.

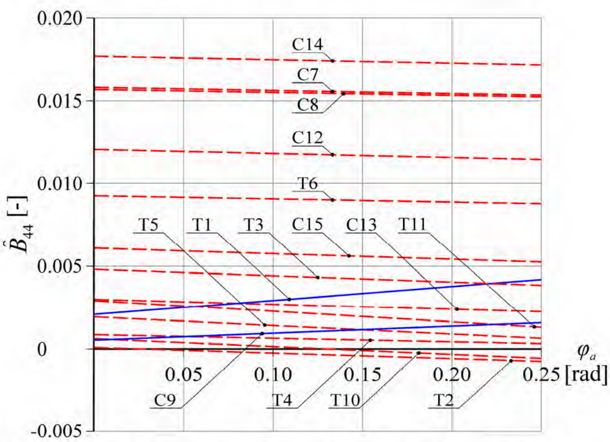

Figure 1: Total roll damping of examined ships as a function of roll amplitude φ_a, according to simplified Ikeda's method

A closer examination of components revealed that in all the cases analyzed (again, except for sample vessels T1 and C9), eddy making component was negative. The focus of investigation thus turned to the eddy damping.

Eddy damping is calculated as follows:

$$\hat{B}_E = \frac{4\hat{\omega} \cdot \varphi_a}{3\pi \cdot x_2 \cdot x_1^{\,3}} \cdot C_R\,, \tag{3}$$

where:

$$C_R = A_E \cdot \exp\left(B_{E1} + B_{E2} \cdot x_3^{B_{E3}}\right), \tag{4}$$

and

$$A_E = f(x_1, x_2),\ B_{E1} = f(x_1, x_2, x_4),$$
$$B_{E2} = f(x_2, x_4),\ B_{E3} = f(x_1, x_2),$$

while $x_1 = B/d$, $x_2 = C_B$, $x_3 = C_M$, $x_4 = OG/d$.

From formula (3) it may be concluded that eddy damping could be negative only if C_R becomes negative. Furthermore, C_R given by formula (4) could be negative only if A_E becomes negative. Therefore, it would be interesting to examine the structure of the formula for the computation of A_E:

$$\begin{aligned} A_E &= A_{E1} + A_{E2} = \\ &= \underbrace{(-0.0182 \cdot x_2 + 0.0155) \cdot (x_1 - 1.8)^3}_{A_{E1}} - \\ &\underbrace{-79.414 \cdot x_2^4 + 215.695 \cdot x_2^3 - 215.883 \cdot x_2^2 + \\ &+93.894 \cdot x_2 - 14.848}_{A_{E2}} \end{aligned} \tag{5}$$

If the geometric properties of an examined ship i.e. B/d and C_B remain within the boundaries of method applicability, A_{E1} cannot become negative. However, A_{E2} may become both negative and larger than A_{E1} in case $C_B > 0.84$, whereby the exact value of this "critical" block coefficient depends on B/d ratio. A_E as a function of B/d and C_B is given in Fig. 2. Now it is possible to explain the principal difference in eddy making component (and, consequently, the total roll damping) between ships T1 and C9 and the rest of the sample vessels: T1 and C9 are the only ships with $C_B < 0.84$.

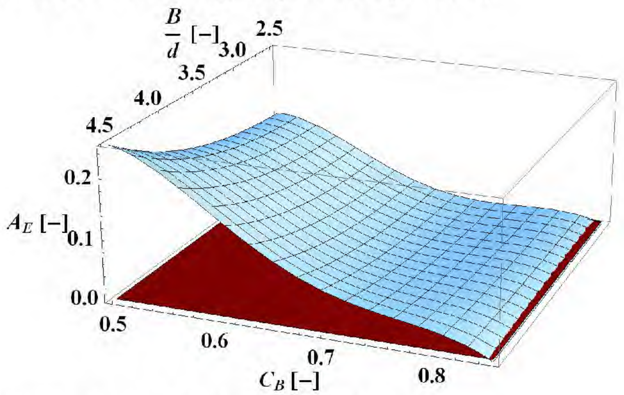

Figure 2: A_E as a function of B/d and C_B

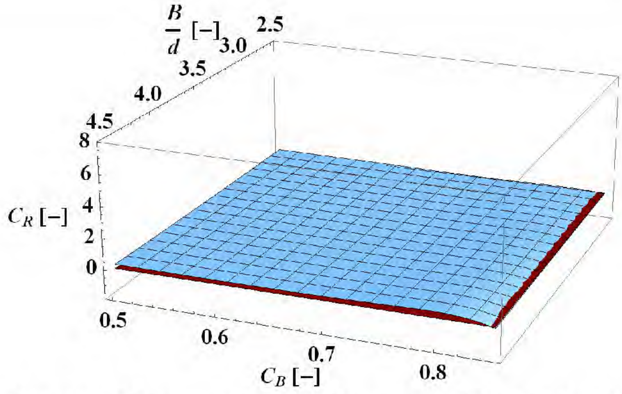

Figure 3: C_R computed over the applicability domain of simplified Ikeda's method, OG/d = 0.2, C_M = 0.9

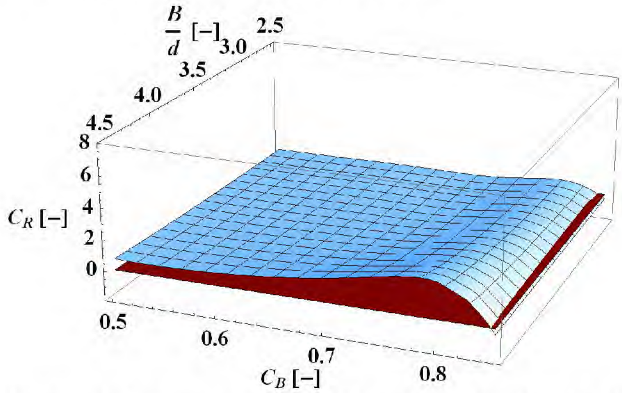

Figure 4: C_R computed over the applicability domain of simplified Ikeda's method, OG/d = 0.2, C_M = 0.99

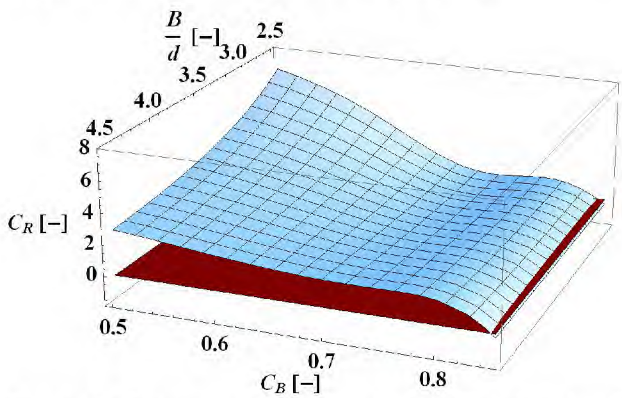

Figure 5: C_R computed over the applicability domain of simplified Ikeda's method, OG/d = -1.5, C_M = 0.9

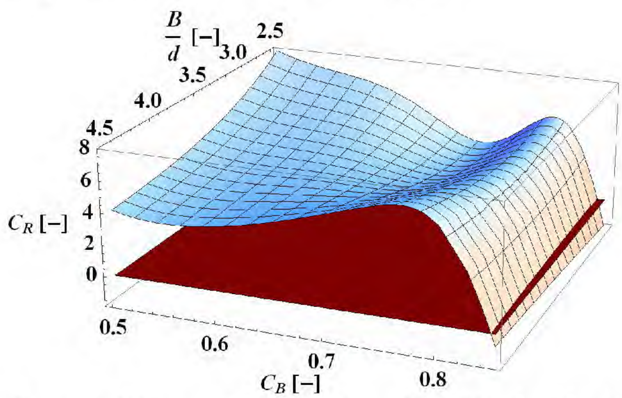

Figure 6: C_R computed over the applicability domain of simplified Ikeda's method, OG/d = -1.5, C_M = 0.99

The factor C_R computed over the complete domain of applicability of simplified Ikeda's method is given in Fig. 3 to Fig. 6. In line with the analysis of formulas (4) and (5), C_R is negative for high values of C_B regardless of B/d, OG/d and C_M. Another interesting feature is noticeable: the sign of the partial derivative of the function (4) with respect to C_B changes when block coefficient attains sufficiently high value. This happens at C_B = 0.74 ÷ 0.81 (depending on OG/d and C_M values) and becomes particularly evident for high mid-ship coefficients C_M.

Therefore, while the eddy making component of damping and, consequently, the total roll damping corresponding to $C_B > 0.84$ are obviously incorrect, it is also questionable whether B_{44} calculated with simplified Ikeda's method could be considered reliable in a much wider range of block coefficients, i.e. $0.74 < C_B < 0.84$. Thus, the issue of accuracy of the simplified method is not limited to inland vessels only, but may also concern seagoing ships with high block coefficients, otherwise believed to be covered by the method.

Classic Ikeda's method

It would be interesting to examine the possibility to amend the simplified Ikeda's method, so as to get more reliable prediction of eddy making component of damping for ships with high C_B, and ultimately for inland vessels.

A_{E2} as defined by equation (5) as well as some possible modifications are shown in Fig. 7. Obviously, there is an array of possibilities for adjustment of the function in the examined range of block coefficients.

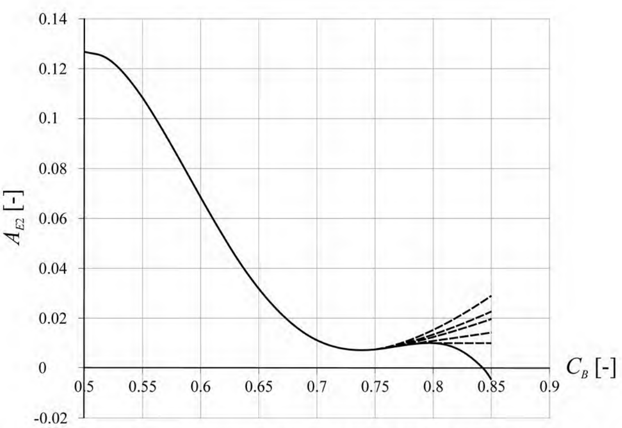

Figure 7: A_{E2} calculated by formula (5) (full line) and possible corrections (dashed lines)

In absence of experimental data, the appropriate modification of function A_{E2} could be sought by calculating eddy damping using the classic Ikeda's method and comparing it to the results obtained by a proposed amendment.

Unlike its simplified version, the classic Ikeda's method requires the knowledge of detailed hull geometry, that is, geometric particulars of cross-sections: sectional breadth B_s and draught d_s, sectional area coefficient σ, bilge radius r_b, and the local maximal distance between the roll axis and hull surface r_{max}. For this purpose, four vessels were selected from Table 1, whose body plans are given in Fig. 8. Two seagoing tankers with high block coefficients (Table 2) were considered as well. Eddy making component computations were performed using 51 equidistant cross sections. Block coefficients of the selected ships are in the range C_B = 0.798 ÷ 0.851.

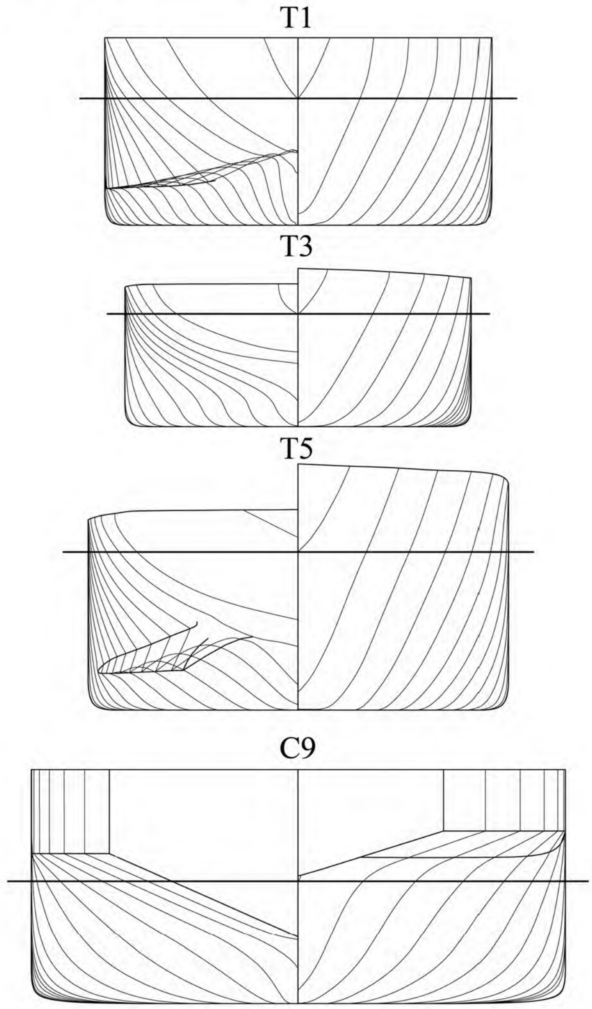

Figure 8: Inland vessels used in computation of eddy making component according to the classic Ikeda's method

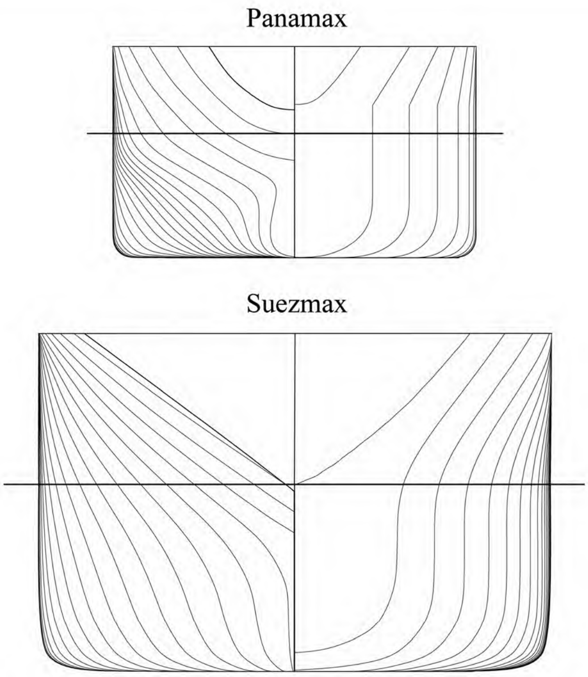

Figure 9: Seagoing tankers used in computation of eddy making component according to the classic Ikeda's method

Table 2: Sample seagoing tankers.

Vessel	L [m]	B [m]	d [m]	C_B	B/d
Panamax	287.78	32.20	11.00	0.8430	2.927
Suezmax	230.07	45.52	16.60	0.7982	2.742

It should be noted that in the classic method, the pressure distribution on the hull surface is obtained assuming the cross sections are approximated by Lewis forms. Clearly, this is not a proper approximation for a number of aft cross sections of examined inland vessels. Therefore, although the proposed procedure seems to be simple, it is not free from challenges.

With respect to that, it should be noted that for cross sections of certain geometric characteristics, (typically for combinations of high beam-to-draught ratios and relatively low area coefficients) sectional eddy damping calculated by the classic Ikeda's method could also be negative. This is often the case with forward- and aft-most cross sections of inland vessels. A trivial solution (and it seems, the usual remedy, see Kawahara et al, 2009) for this deficiency is to take the damping of a "problematic" cross section as zero. Having no possibility to estimate a correct value of eddy damping corresponding to such cross sections, the same approach was used in this paper.

3. A POSSIBLE ADJUSTMENT OF SIMPLIFIED FORMULA FOR EDDY MAKING COMPONENT OF DAMPING

In order to find an appropriate adjustment of formula (5), the following procedure is proposed. Assuming that, for each ship, it may be established:

$$B_{E(s)} \approx B_{E(c)}, \tag{6}$$

(where "*s*" stands for simplified and "*c*" stands for classic method) it would be possible to extract the "correct" value of A_{E2} corresponding to a given (high) block coefficient, provided that $B_{E(c)}$ is calculated beforehand.

$B_{E(c)}$ is obtained by numerical integration of sectional eddy damping over the ship length:

$$B_{E(c)} = \int_L B'_{E(c)} dx, \tag{7}$$

where

$$B'_{E(c)} = \frac{4 \cdot \omega \cdot \varphi_a}{3\pi} \cdot \rho d_s^4 \cdot C_{R(c)}. \tag{8}$$

The sectional $C_{R(c)}$ depends on B_s and d_s, σ, r_b, r_{max}, OG as well as pressure coefficient C_P. More precisely:

$$C_{R(c)} = \left(\frac{r_{\max}}{d_s}\right)^2 \cdot f\left(\frac{r_b}{d_s}, \frac{B_s}{2d_s}, \sigma, \frac{OG}{d_s}\right) \cdot C_P. \tag{9}$$

Given the complexity of the procedure for the calculation of r_b, r_{max} and C_P, the respective expressions are omitted from the present paper, but may be found in e.g. Falzarano et al (2015), who presented the consolidated formulas of the classic method. On the other hand, eddy damping of a ship, according to the simplified method, is:

$$B_{E(s)} = \frac{4 \cdot \omega \cdot \varphi_a}{3\pi} \cdot \rho d^4 \cdot L \cdot C_{R(s)}, \tag{10}$$

where $C_{R(s)}$ is defined by equation (4). From equations (6) ÷ (8) and (10) it follows:

$$C_{R(s)} = \frac{1}{d^4 L} \int_L d_s^4 \cdot C_{R(c)} dx. \tag{11}$$

Then, using the formulas (4), (5) and (11), an estimate of A_{E2} may be obtained for a given ship.

Finally, using the described procedure, A_{E2} values were calculated for the selected inland vessels (see Fig. 10).

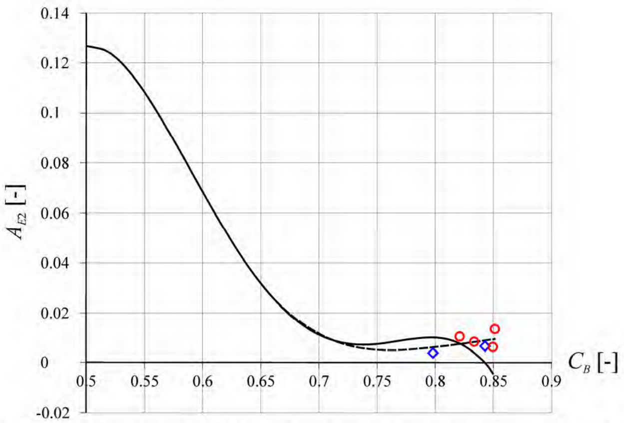

Figure 10: A_{E2} calculated by formula (5) (full line) and proposed correction given by formula (12) (dashed line). Circles represent the values calculated for inland vessels, while diamonds correspond to seagoing tankers.

Based on these results, a new expression for A_E, valid in the whole range of applicability of the simplified Ikeda's method, is proposed:

$$\begin{aligned} A_{E-new} &= A_{E1} + A_{E2-new} = \\ &= \underbrace{(-0.0182 \cdot x_2 + 0.0155) \cdot (x_1 - 1.8)^3}_{A_{E1}} + \\ &\underbrace{+151.48 \cdot x_2^5 - 567.603 \cdot x_2^4 + 840.297 \cdot x_2^3 - \\ &-612.498 \cdot x_2^2 + 218.904 \cdot x_2 - 30.497}_{A_{E2-new}} \end{aligned} \tag{12}$$

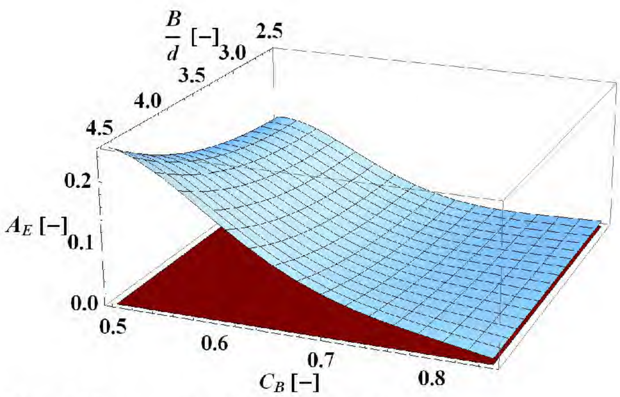

Figure 11: A_{E-new} as a function of B/d and C_B.

A_{E-new} as a function of B/d and C_B is given in Fig. 11. The factor C_R adjusted by formula (12) is computed within the range of applicability of the simplified Ikeda's method and given in Fig. 12 and Fig. 13. Finally, the non-dimensional equivalent linear total roll damping of the sample ships given in Table 1 is computed using the adjusted simplified formula for eddy damping, see Fig. 14. Whenever the block coefficient exceeded the applicability range, the calculations were carried out with $C_B = 0.85$. As it can be seen in Fig. 14, the total roll damping attains an increasing trend with respect to roll amplitude, as it should be normally expected.

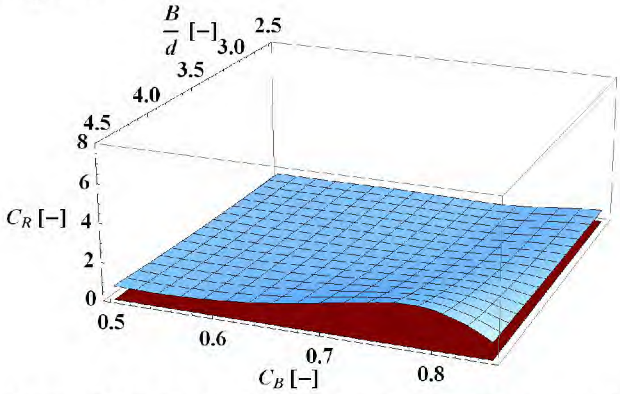

Figure 12: Factor C_R adjusted by formula (12) computed over the applicability domain of simplified Ikeda's method, $OG/d = 0.2$, $C_M = 0.99$.

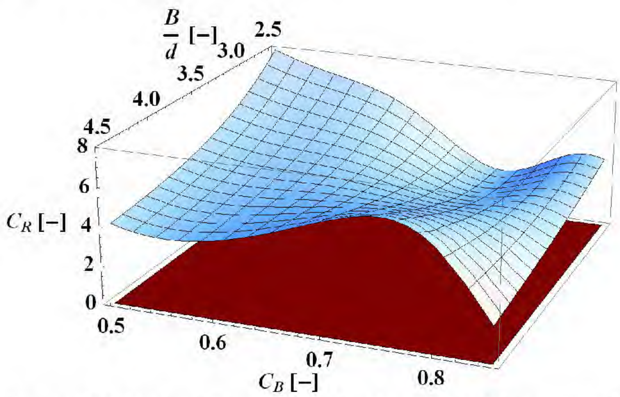

Figure 13: Factor C_R adjusted by formula (12) computed over the applicability domain of simplified Ikeda's method, $OG/d = -1.5$, $C_M = 0.99$.

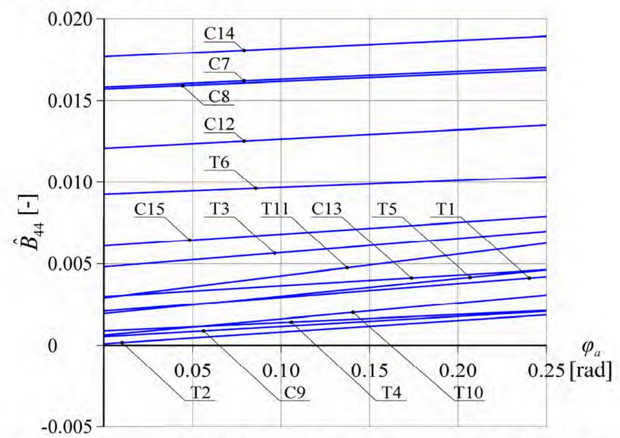

Figure 14: Total roll damping of examined ships as a function of roll amplitude φ_a, according to simplified Ikeda's method, taking into account proposed adjustment of eddy damping component

4. FURTHER EXTENSION OF SIMPLIFIED FORMULA FOR EDDY DAMPING TO INLAND VESSELS

It was already pointed out that most of the sample vessels given in Table 1, and most of inland vessels in general, fall out of the range of applicability of simplified Ikeda's method with respect to B/d and C_B. For instance, beam-to-draught ratios of typical European river cruisers are in the range of 5.5 ÷ 8.5. Therefore, without model tests, it appears difficult to adjust the simplified Ikeda's method so as to extend its applicability to just any inland vessel.

For the sake of comparison, for some sample vessels having $C_B > 0.85$ (see Table 3), $C_{R(s)}$ was calculated by using formula (11), based on classic Ikeda's method, taking into account actual hull form geometry (corresponding to real C_B) in the computation of $C_{R(c)}$. These figures are subsequently compared to data obtained by applying the simplified formula (4) using both expression (5) for A_E and the proposed adjustment of A_E given by (12); in these two latter cases, $C_B = 0.85$ is always used, instead of actual block coefficients.

Table 3: Discrepancies in estimation of eddy making component using different formulas and limitations. All calculations were carried out for $OG = 0$ m.

		$C_{R(s)}$		
Vessel	C_B	(4) + (5)	(4) + (12)	(11)
T2	0.9226	-0.3773	0.7846	4.6228
T4	0.8535	-0.3876	0.8808	6.3669
C8	0.8664	-0.3744	0.9480	3.5575
C12	0.9031	-0.3862	0.8927	2.6430
C15	0.9101	-0.3884	0.8386	3.5152

Significant discrepancies between the values of C_R obtained using different approaches indicate that an accurate estimation of eddy making component of such full-bodied vessels remains a task for the future. For the time being, however, if the simplified Ikeda's method is employed, it is suggested to use the adjusted eddy damping formula (proposed in the paper and based on (12)) applying the method limitations whenever the geometric properties of the analyzed hull exceed the applicability range.

5. CONCLUDING REMARKS

In the course of investigation of applicability of the simplified Ikeda's method for roll damping prediction to European inland vessels, it was found that the eddy damping formula fails to properly predict the corresponding damping component if the block coefficient of the vessel is sufficiently large, i.e. $C_B > 0.8$. This deficiency is particularly striking for $C_B > 0.84$, when eddy making component of damping becomes negative.

Therefore, an adjustment of the simplified formula for eddy making component prediction is proposed, based on calculations performed using the classic Ikeda's method. The method was applied to several typical inland hulls with high block coefficients ($C_B = 0.82 \div 0.85$) and high mid-ship coefficients ($C_M \geq 0.99$), covering a complete range of applicability of the simplified method with respect to beam-to-draught ratios ($B/d = 2.6 \div 4.4$). Two typical seagoing tankers (having $C_B \approx 0.8$ and $C_B \approx 0.84$) were included in the calculations as well. It is expected that the derived expression could extend the applicability of the simplified Ikeda's method to inland ships, in absence of adequate experimental data.

Furthermore, it is believed that the adapted formula provides a better estimation of eddy damping component not only for inland vessels but also for seagoing ships with full hull forms.

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