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PREDICTION OF THE NATURAL FREQUENCY OF SHIP'S ROLL WITH REGARD TO VARIOUS MODELS OF ROLL DAMPING

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Abstract

One of the most important dynamic phenomenon recognized as dangerous to seagoing ships is the resonance gain of rolling. This may occur due to nonlinearity of ship response in resonance conditions, i.e. when the encounter wave frequency is similar to the natural frequency of ship roll motion. Such coincidence should be avoided therefore shipmaster steers clear of some configurations of speed and course resulting in potential synchronous rolling. Nowadays, according to the IMO Intact Stability Code the natural period of roll is determined with the use of very simplified GM-based formula. The paper deals with the problem of more sophisticated prediction of ship's natural rolling frequency with the use of the one degree-of-freedom roll equation with regard to nonlinear restoring moment. A special emphasis is put on the damping coefficient modelling which remains one of the crucial issues in terms of rolling simulation. Two typical approaches to the damping coefficient estimation are tested, the linear and the nonlinear one according to Ikead's method. The set of ship roll simulations is carried out for a wide range of excitation frequency and a variety of exciting moment. The results of computation focused on the natural frequency of ship roll prediction are compared to assess the influence of damping model selection.

Keywords: *sea transport, ship stability, ship rolling, roll damping coefficient*

1. Introduction

In regards to ship stability-related safety, the greatest concern refers to her rolling oscillations where the nonlinear effects are key issues related to ship motion in rough sea conditions. Potentially dangerous motion that may cause capsizing of an intact ship or reaching excessive angles of her heel can be divided into resonant and non-resonant ones [1]. The non-resonant situation is mainly the outcome of two possible scenarios. First of all, they are caused by a combination of the ships rolling motion and the dynamic action of gusty wind. This scenario is quite well described by the weather criteria of stability in accordance with the Intact Ship Stability Code [12]. Second, they are caused by the loss of stability when sailing on following or quartering seas when the wave crest is amidships. Furthermore, broaching and surf riding may be classified as non-resonant phenomena, which may lead to ship capsizing.

The resonant situations may be divided into parametric resonance and synchronous rolling [1], [17]. The first one occurs mainly on following and quartering seas and it is caused by inducing instability and an increase in rolling amplitude due to the periodic variation of ships stability characteristics, not as a direct result of roll excitation. The worldwide records evidence only one unambiguous and a few suspected cases of the parametric rolling experienced by large vessels while the synchronous rolling of ships is a part of a typical experience of almost all mariners.

The synchronous rolling, in turn, takes place due to direct excitation when the encounter wave period is close to the natural period of ship's roll. Not very often, this mode of rolling causes substantial losses because usually officers of the watch being aware of the hazard repress development of the excessive motion just by mistuning (usually by alternation of the ships heading causing a change of wave aspect and encounter frequency). Such an action should be a routine response to the synchronous rolling, however it is only feasible on the spot while it would be safer to predict it in advance and avoid such situations at all. Thus, the effective prediction of the synchronous rolling seems to be profitable.

2. Modelling of ship roll motion

The prediction of ship's synchronous rolling is strictly related to the credible mathematical modelling of ship motion. Numerous works deal with various mathematical models of ship motion and the impact of respective components notation on the results of numerical simulations [2, 21, 23, 25]. Some analysed one-degree-of-freedom models regard only the rolling and others comprehend three or six degrees-of-freedom comprising couplings between individual motions [2, 5, 15, 16]. The importance of the mathematical model formulation to be utilized in the course of ship motion calculations is revealed in the benchmark study carried out by Spanos and Papanikolaou [19]. This work presents a comparison of calculation results performed for ships parametric rolling on waves. Fourteen different and well-recognized simulation programs were assessed and the consistency of many results left much to be desired giving room for further researches in this field.

One of the crucial components of the ship motion equations refers to the damping moment, which is especially important for rolling since the damping crucially determinates the amplitude of roll for an assumed sea waves height. However, damping is related to truly complex phenomena therefore it generates a number of challenges due to its nonlinear characteristics. For a long time the roll damping has been a subject of many researches [4, 10, 11]. The canonical work in this field is published by Himeno [11] and it presents systematic analysis of various approaches towards modelling of roll damping. Later works present the comparison of roll simulations results obtained with the use of different damping models [3, 22]. Roll damping coefficients can be hardly determined only in the course of theoretical calculation. Thus, combining the numerical simulations and experimental tests is the most effective approach nowadays. The basic test usually performed is a free-roll decay experiment [13, 18, 24].

The mathematical modelling of ships rolling leads to the numerical simulations enabling an estimation of a ship response to an exciting moment. The nonlinearity of ship response observed as a rapid growth of rolling amplitude, intensifies for frequencies close to the resonant mode of motion, which is a subject for researches for a long time [6, 20, 21]. One of the most astonishing phenomenon emerging in the resonance span of rolling is an amplitude bifurcation, which has been studied for a long time [8, 9]. Some bifurcations episodes were also confirmed in the experimental tests [9].

The ships roll resonance remains an essential issue related to the safety of navigation. It develops for a specific range of roll frequencies reflecting the tuning to the external excitation. In many papers the ship natural frequency of roll, which determines the resonance mode of motion, is used as one of the rolling equation parameters. This frequency is typically calculated based on the initial metacentric height of a ship, most often with the use of a simple formula recommended in the IMO IS Code [12]:

$$\tau = \frac{2 \cdot c \cdot B}{\sqrt{GM_0}}, \tag{1}$$

with the value of c coefficient:

$$c = 0.373 + 0.023 \cdot \frac{B}{T} - 0.00043L, \tag{2}$$

where:

c – coefficient describing ships transverse gyration radius r_x (the radius of gyration equals $r_x = c \cdot B$),

B – ship's breadth,

L – ship's length at waterline,

T – mean ship's draft,
GM_0 – initial transverse metacentric height.

The initial metacentric height present in formula (1) is valid for small angles of heel, normally up to about five to seven degrees. Such small rolling amplitude does not pose a threat to the ships stability. As safety analyses are required and the truly risky amplitudes of roll need to be considered, the utilization of the initial metacentric height is rather problematic. The large amplitudes of roll should be rather considered with the use of the motion equation.

3. Applied mathematical model of ship rolling

The research described in this paper aims at the resonance roll characteristics, which are obtained based on the roll motion equation. The literature review provide that the most commonly used model of ship's rolling, which neglects any couplings between motions taking place in other than rolling degrees of freedom may be given by the following formula:

$$(I_x + A_{44})\ddot{\phi} + B_e\dot{\phi} + K(\phi) = M_w cos(\omega_e t), \tag{3}$$

where:
ϕ – angle of ship's heel,
I_x – transverse moment of ship's inertia,
A_{44} – moment of added mass due to water dragging by the rolling hull,
B_e – equivalent roll damping component,
$K(\phi)$ – righting moment e.g. stiffness of the ship,
M_w – external heeling moment exciting ship's rolling,
ω_e – encounter frequency of waves (or any other origin of the moment arousing ship rolling),
t – time.

The kind of roll damping modelling, which is applied in the formula (3), is used quite often in studies on ship rolling, however the nonlinear approach is recently being utilized by many authors. Although, the roll damping is significantly nonlinear and the equivalent linear roll damping coefficient B_e depends on the amplitude and the frequency and the ship's speed [11, 24], in many scientific works the coefficient B_e is assumed to be constant regardless the parameters of roll motion. Both approaches are examined in this research.

For practical purposes, the equation of ship rolling given by the formula (3) would not be really convenient, thus it is transformed in the course of some substitution to the mathematical model of ship rolling given in the following notation:

$$\ddot{\phi} + 2\mu \cdot \dot{\phi} + \frac{g}{r_x^2} GZ(\phi) = \xi_w cos(\omega_e t), \tag{4}$$

where:
μ – roll damping coefficient,
g – gravity acceleration,
r_x – gyration radius of a ship and added masses,
ξ_w – exciting moment coefficient,
all remaining symbols like in the formula (3).

Since the main purpose of the conducted research is to assess the influence of the various approaches to roll damping modelling on the resultant synchronous rolling frequency, the linear and nonlinear models of damping are applied. The linear model is realized by entering the constant value of the μ coefficient in the equation (4). According to the literature this set value equals μ=0,05. In turn, the nonlinear model of damping conditioning the value of the μ coefficient on the actual roll amplitude is based on the Ikeda's method, being one of the most popular and well examined [7].

The roll damping prediction method, which is now called Ikeda's method, divides the damping into the frictional, the wave, the eddy and the bilge keel components [14]:

$$B_e = B_F + B_W + B_E + B_{BK}, \tag{5}$$

where:
B_F – frictional damping component,
B_W – wave damping component,
B_E – eddy damping component,
B_{BK} – bilge keel damping component.

All listed damping components are calculated according to the available formulas producing the non-dimensional values (marked by a dash) which can be referred to a particular ship with the use of following formulas [14]:

$$\hat{B}_e = \frac{B_e}{\rho D B^2}\sqrt{\frac{B}{2g}}, \quad \hat{\omega} = \omega\sqrt{\frac{B}{2g}}, \tag{6}$$

where:
ρ – water density,
D – displacement of a ship,
B – ship's breadth,
g – gravity acceleration.

The values of individual damping components depend on the ship characteristics, which are constant since the ship geometry does not change, and on actual roll characteristics like the amplitude and the frequency, as follows [14]:

$$\hat{B}_F = f(\phi_A, \hat{\omega}), \tag{7}$$

$$\hat{B}_W = f(\hat{\omega}), \tag{8}$$

$$\hat{B}_E = f(\phi_A, \hat{\omega}), \tag{9}$$

$$\hat{B}_{BK} = f(\phi_A, \hat{\omega}), \tag{10}$$

where:
ϕ_A – actual amplitude of ship's roll,
$\hat{\omega}$ – non-dimensional frequency of roll.

The limitations of Ikeda's method are mainly related to the hull forms. The prediction formulas were originally elaborated for typical hulls of those times while the number of ships that have buttock flow stern, such as large passenger ship or pure car carrier, has been increasing [14]. The accuracy of Ikeda's method drops for such modern hulls; therefore, for the purpose of this study a conventional general cargo vessel is preferred.

4. Considered ship particulars

The ship taken into account in the course of the research is a medium-size Polish general cargo vessel project B-354 build in Gdynia Shipyard. She is 140 m long, 22 m wide with the draft 9 m reflecting almost fully loaded cargo holds (the summer draft equals 9.14 m). The assumed initial metacentric height equals GM_0=1.00 m which is typical for the considered loading conditions according to the Ship Stability Booklet. The general view of the ship is shown in Fig. 1 on the left and her body plan on the right side.

According to the roll equation (4) there are three key elements resulting in ship characteristics in terms of her rolling, e.g. the roll damping coefficient, the radius of gyration and the righting arm curve. The radius of gyration is assumed constant in all performed computations and it equals $r_x = c \cdot B$ where c means the coefficient according to the formula (2) and B is ship beam. The righting arm curve depends on ship's loading conditions, which are selected based on the Ship stability Booklet and on the shape of the hull. The utilized GZ curve is presented in Fig. 2 on the right side. The damping coefficient calculated according to Ikeda's method is shown in Fig. 2 on the left side.

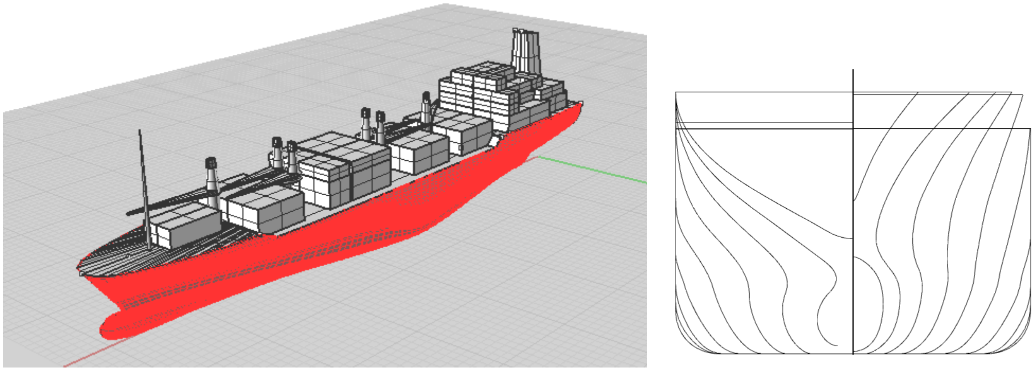

Fig. 1. Ship project B-354 – 3D numerical model (left) and her body plan (right)

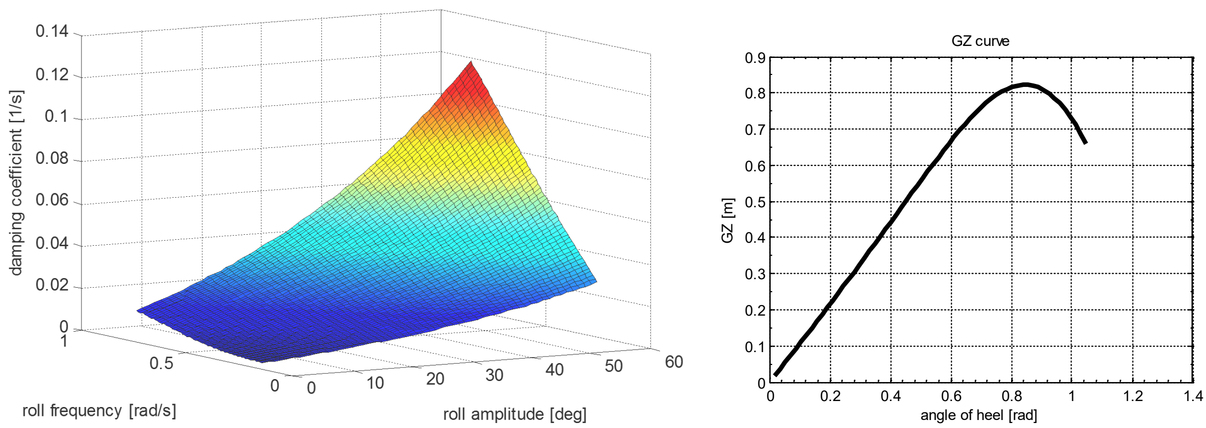

Fig. 2. Roll damping coefficient according to Ikeda's method for B-354 ship in the considered loading condition (left) and GZ curve (right)

5. Results of computations

Numerous simulations of ship rolling are run to obtain roll response to a variety of excitations. The outcome of every single simulation is just the history of roll, which is shown in Fig. 3.

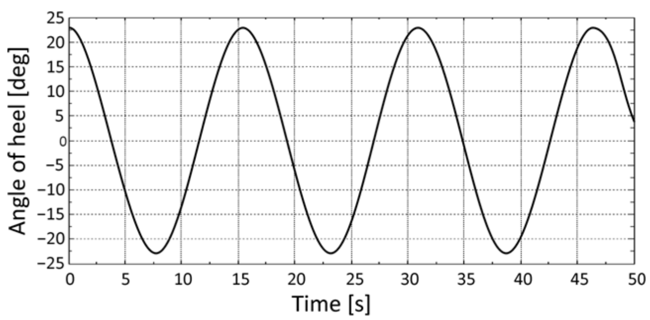

Fig. 3. Exemplary outcome of the roll simulation, e.g. the history of ship's rolling

A set of performed roll simulations run for a range of exciting moment frequencies and amplitudes enables to obtain the roll response curves for the considered vessel in her assumed loading condition. The resonance frequency of roll cannot be represented by a single number but by the back-bone curve, tracing the maxima of roll amplitude characteristics, so such back-bone curves are plotted [26]. The results obtained for the constant value of linear damping coefficient are shown in Fig. 4 and for the nonlinear damping coefficient calculated according to Ikeda's method are shown in Fig. 5.

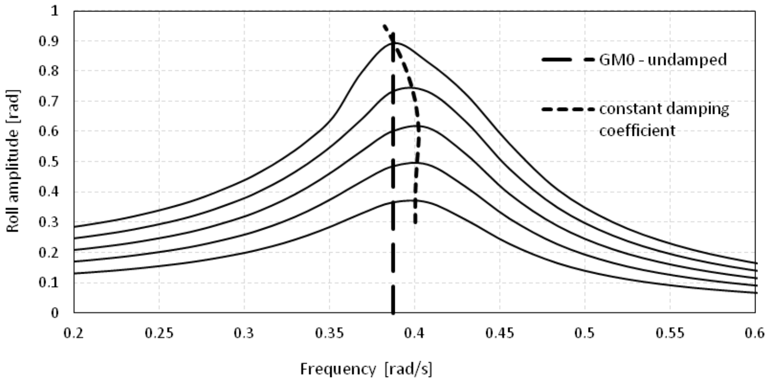

Fig. 4. Set of amplitude response curves obtained for increasing value of the excitation moment with the constant value of the damping coefficient and the backbone curve

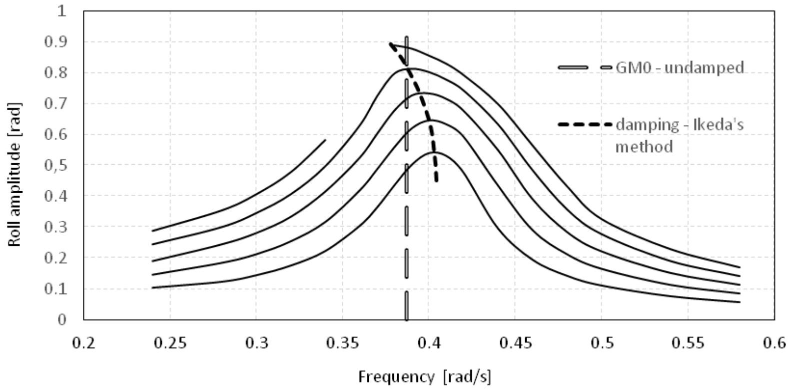

Fig. 5. Set of amplitude response curves obtained for increasing value of the excitation moment with the damping coefficient modelled according to Ikeda's method and the backbone curve

The most informative in terms of the assessment of influence of the roll damping modelling is direct comparison of the obtained backbone curves, which is shown in Fig. 6. Additionally, the synchronous roll frequency calculated based on the formula (1) is plotted.

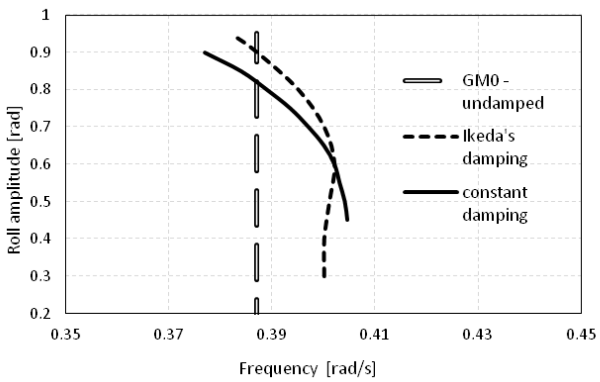

Fig. 6. Comparison of the backbone curves obtained based on roll simulations with the use of linear and nonlinear damping coefficient

Since the backbone curve traces the maxima of roll response curves obtained for the full range of exciting moment, it presents the combination of the frequency and the amplitude of ship's roll motion in the most dangerous mode, e.g. the resonance. Thus, the information proceeding from the depicted in Fig. 6 curves would be appreciated by a captain when avoiding entering the roll resonance zone.

6. Summary and conclusions

The conducted research deals with roll damping modelling which is one of the crucial issue related to the ship-rolling problem. The linear approach with the constant value of the damping coefficient is applied as well as the nonlinear approach based on Ikeda's method. The roll response characteristics are achieved in the course of numerical simulations carried out for both considered options of damping modelling. The study is focused on the ship synchronous rolling being the significant phenomenon to be avoided when underway.

The result of the research is depicted in the form of two backbone curves obtained based on roll amplitude response curves. It may be noticed that these curves vary, although the significance of the studied is rather limited. In turn, the resonance frequency of ship roll calculated according to the contemporary recommended by IMO formula (1) disagrees considerably from the results of numerical simulation of roll.

The knowledge of the ship roll resonance frequency is an essential element of save passage planning and completing therefore there is a potential to implement a decision support tool based on roll modelling. If so, the roll equation needs to be utilized and both damping models can be effectively applied, e.g. linear and nonlinear one while the formula (1) should be avoided due to the lack of accuracy. Considering the practical application, it may be noticed that the analytical method for the backbone curve prediction could be also worked out with pragmatic profits.

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