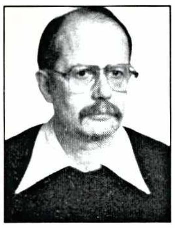

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Ship roll damping moments

SUMMARY

In the paper a nonlinear form of the ship's roll damping moment and an equivalent linear damping moment is introduced.

By comparison of the action of both moments during one quadrant of the roll period an expression was found linking the equivalent linear damping moment with the nonlinear roll coefficient.

The equivalent linear roll damping moment coefficient can be calculated from model tests on the basis of the roll decay characteristics.

Presented are also exemplary calculations of the nonlinear roll damping coefficients for a model of the passenger ferry POLONIA. Their results are given in a graphical form.

INTRODUCTION

Knowledge of the roll damping coefficient is required particularly in the case of numerical simulations of ship motions. The coefficient consists of a potential and a viscous part and to calculate it numerically is not easy. For this reason model tests are often applied. The model tests are also used to verify calculations of the damping coefficient obtained by means of numerical calculation. This paper presents an identification method of the nonlinear roll damping coefficient of a ship's model on the basis of recording its roll decaying process.

The identification of the nonlinear roll damping coefficient is also discussed in the papers [4] , [5] and [6].

NONLINEAR FORM OF THE DAMPING COEFFICIENT

The nonlinear damping moment can be expressed in the form of power series [1] :

$$M_N = 2(I_X + m_\Phi)\,\delta_\Phi\left(\dot\Phi + \frac{\varepsilon_1}{\omega_\Phi}\dot\Phi|\dot\Phi| + \frac{\varepsilon_2}{\omega_\Phi^2}\dot\Phi^3 + \frac{\varepsilon_3}{\omega_\Phi^3}\dot\Phi^3|\dot\Phi| + \ldots\right) \tag{1}$$

The same moment acting within a short time interval can be written in the form of an equivalent linear damping moment :

$$M_L = 2(I_X + m_\Phi)\,\delta_\Phi^L\dot\Phi \tag{2}$$

It is assumed that for one quadrant of the free roll period, i.e. for phase angle

$$0 < \omega_\Phi t < \frac{\pi}{2}$$

the roll angle $\Phi(t)$ changes sinusoidally :

$$\begin{aligned}\Phi &= \Phi_A \sin\omega_\Phi t\\ \dot\Phi &= \Phi_A\,\omega_\Phi\cos\omega_\Phi t\end{aligned} \tag{3}$$

In this quadrant of the roll period the following relations hold :

$$\begin{aligned}\dot\Phi\,|\dot\Phi| &= \dot\Phi^2\\ \dot\Phi^3|\dot\Phi| &= \dot\Phi^4\end{aligned} \tag{4}$$

In order to determine the nonlinear roll damping coefficients ε_1 , ε_2 , ... the work of the nonlinear damping moment M_N is compared with that of the equivalent linear damping moment M_L in one quadrant of the roll period :

$$\int_0^{\frac{\pi}{2}} M_N\,d(\omega_\Phi t) = \int_0^{\frac{\pi}{2}} M_L\,d(\omega_\Phi t) \tag{5}$$

By introducing the variable : $\alpha = \omega_\Phi t$
the following right-hand side term of equality (5) can be obtained :

$$R = \int_0^{\frac{\pi}{2}} M_L d\alpha =$$

$$= \int_0^{\frac{\pi}{2}} 2(I_X + m_\Phi)\,\delta_\Phi^L \Phi_A\,\omega_\Phi \cos\alpha\, d\alpha = \tag{6}$$

$$= 2(I_X + m_\Phi)\,\delta_\Phi^L \omega_\Phi$$

On the other hand, the left-hand side term of equality (5) takes the form :

$$L = \int_0^{\frac{\pi}{2}} M_N d\alpha = \int_0^{\frac{\pi}{2}} 2(I_X + m_\Phi)\,\delta_\Phi (\Phi_A\,\omega_\Phi \cos\alpha +$$

$$+ \frac{\varepsilon_1}{\omega_\Phi}\Phi_A^2\,\omega_\Phi^2 \cos^2\alpha + \frac{\varepsilon_2}{\omega_\Phi^2}\Phi_A^3\,\omega_\Phi^3 \cos^3\alpha +$$

$$+ \frac{\varepsilon_3}{\omega_\Phi^3}\Phi_A^4\,\omega_\Phi^4 \cos^4\alpha + \frac{\varepsilon_4}{\omega_\Phi^4}\Phi_A^5\,\omega_\Phi^5 \cos^5\alpha + \ldots)\,d\alpha =$$

$$= 2(I_X + m_\Phi)\,\delta_\Phi \Phi_A\,\omega_\Phi (\int_0^{\frac{\pi}{2}} \cos\alpha\, d\alpha + \tag{7}$$

$$+ \varepsilon_1 \Phi_A \int_0^{\frac{\pi}{2}} \cos^2\alpha\, d\alpha + \varepsilon_2 \Phi_A^2 \int_0^{\frac{\pi}{2}} \cos^3\alpha\, d\alpha +$$

$$+ \varepsilon_3 \Phi_A^3 \int_0^{\frac{\pi}{2}} \cos^4\alpha\, d\alpha + \varepsilon_4 \Phi_A^4 \int_0^{\frac{\pi}{2}} \cos^5\alpha\, d\alpha + \ldots)$$

The integrals appearing in relation (7) can be calculated analytically and they amount to:

$$\int_0^{\frac{\pi}{2}} \cos\alpha\, d\alpha = 1 = 1.00$$

$$\int_0^{\frac{\pi}{2}} \cos^2\alpha\, d\alpha = \frac{\pi}{4} \cong 0.78$$

$$\int_0^{\frac{\pi}{2}} \cos^3\alpha\, d\alpha = \frac{2}{3} \cong 0.67 \tag{8}$$

$$\int_0^{\frac{\pi}{2}} \cos^4\alpha\, d\alpha = \frac{3}{16}\pi \cong 0.59$$

$$\int_0^{\frac{\pi}{2}} \cos^5\alpha\, d\alpha = \frac{8}{15} \cong 0.53$$

$$\ldots$$

$$\int \cos^n\alpha\, d\alpha = \frac{1}{n}\cos^{n-1}\alpha \sin\alpha +$$

$$+ \frac{n-1}{n} \int \cos^{n-2}\alpha\, d\alpha \quad (n \geq 2)$$

By using relations (6) , (7) and (8), the following form of equality (5) is obtained :

$$\delta_\Phi^L = \delta_\Phi \left(1 + \frac{\pi}{4}\varepsilon_1 \Phi_A + \frac{2}{3}\varepsilon_2 \Phi_A^2 + \frac{3\pi}{16}\varepsilon_3 \Phi_A^3 + \frac{8}{15}\varepsilon_4 \Phi_A^4 + \ldots \right) \tag{9}$$

This is the dependence of the equivalent linear roll damping coefficient on the roll amplitude.
This dependence is of the polynomial form.
Writing the nonlinear roll damping coefficient in the form of the expression (9) has the following advantages :

- the expansion coefficients ε_1 , ε_2 , ... are dimensionless
- when $\varepsilon_1 = 0$, $\varepsilon_2 = 0$, ... the linear damping coefficient is obtained.

APPROXIMATION OF THE NONLINEAR ROLL DAMPING COEFFICIENT

The nonlinear equivalent roll coefficient can be determined from model tests of free decaying roll. An example record of roll decay process is shown in Fig.1. The equivalent roll coefficient can be obtained from the following relation:

$$\delta_\Phi^L = \frac{1}{T_\Phi} \ln \frac{\Phi_k}{\Phi_{k+1}} \tag{10}$$

where :
Φ_k , Φ_{k+1} – two successive amplitudes of free decaying roll.

It is also possible to find the introduced non-dimensional equivalent roll damping coefficient ν_Φ^L, defined as follows :

$$\nu_\Phi^L = \frac{\delta_\Phi^L}{\omega_\Phi} \tag{11}$$

The equivalent coefficient depends on the roll amplitude. Usually, the greater the roll amplitude the greater the roll damping coefficient , which implies the nonlinear damping. The measurement results can be presented in the form shown in Fig.2.

The curve shown in Fig.2 represents a polynomial in the form :

$$\delta_\Phi^L = a_0 + a_1 \Phi_A + a_2 \Phi_A^2 + \ldots \tag{12}$$

By comparing the coefficients of polynomials (9) and (12) it is possible to obtain the following relations :

$$a_0 = \delta_\Phi$$

$$a_1 = \frac{\pi}{4}\varepsilon_1\delta_\Phi \qquad a_2 = \frac{2}{3}\varepsilon_2\delta_\Phi \qquad a_3 = \frac{3}{16}\pi\varepsilon_3\delta_\Phi$$

$$a_4 = \frac{8}{15}\varepsilon_4\delta_\Phi \tag{13}$$

....

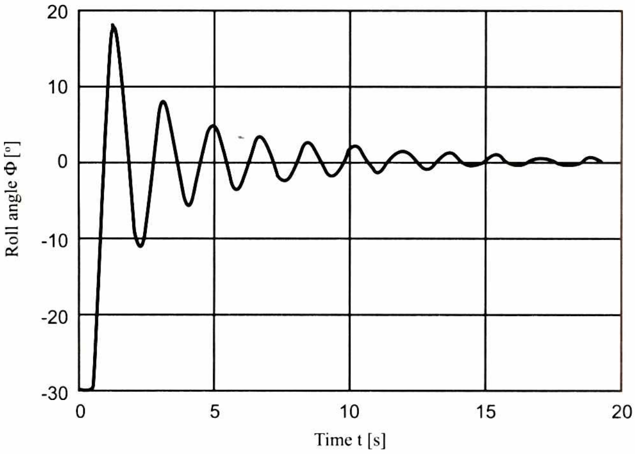

***Fig.1.** Free – roll decay characteristics of the model of intact passenger ferry [2]*

To determine the coefficients a_0 , a_1, ... the mean square approximation is used. This means that the sum of squares of deviations $(\delta^L_\Phi - \delta^L_{\Phi i})$ should be minimized :

$$\Delta_i = a_0 + a_1\Phi_{Ai} + a_2\Phi^2_{Ai} + ... - \delta^L_{\Phi i} \tag{14}$$

$$\sum \Delta_i^2 = \min \tag{15}$$

The approximation can be carried out by choosing optionally only some of the coefficients ε_1 , ε_2 , ... , and rejecting the remaining ones. This is tantamount to the choice of appropriate coefficients a_0 , a_1, ... The coefficient a_0 has to remain. Such mean square approximation with the choice of coefficients ε_1 and ε_2 only is presented below. The polynomial (12) takes then the following form:

$$\delta^L_\Phi = a_0 + a_1\Phi_A + a_2\Phi^2_A \tag{16}$$

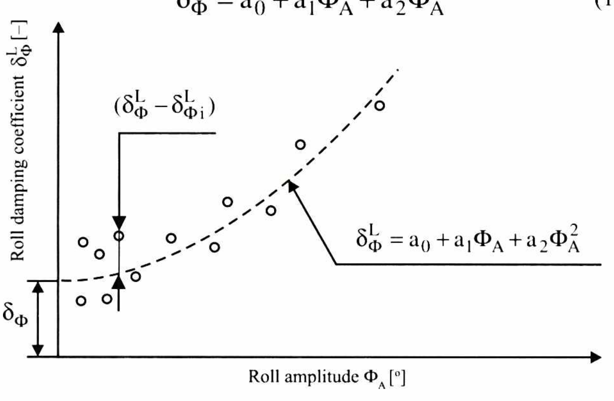

***Fig.2.** Approximation of the nonlinear roll damping coefficient*

Hence, the deviations Δ_i are now expressed by the relation (17), transformed of (14) :

$$\Delta_i = a_0 + a_1\Phi_{Ai} + a_2\Phi^2_{Ai} - \delta^L_{\Phi i} \tag{17}$$

The sum of squares is to reach a minimum. For this purpose the sum (15) should be differentiated with respect to the coefficients a_0 , a_1 and a_2 , and equated to zero, as this is the necessary and sufficient condition for the existence of minimum. In result, the following system of equations can be obtained:

$$\begin{cases} a_0 n + a_1\sum\Phi_{Ai} + a_2\sum\Phi^2_{Ai} = \sum\delta^L_{\Phi i} \\ a_0\sum\Phi_{Ai} + a_1\sum\Phi^2_{Ai} + a_2\sum\Phi^3_{Ai} = \sum\delta^L_{Ai}\Phi_{Ai} \\ a_0\sum\Phi^2_{Ai} + a_1\sum\Phi^3_{Ai} + a_2\sum\Phi^4_{Ai} = \sum\delta^L_{Ai}\Phi^2_{Ai} \end{cases} \tag{18}$$

This is the system of linear algebraic equations with three unknowns. By solving the system the coefficients a_0 , a_1 and a_2 are obtained. After that it is possible to calculate the damping coefficients δ_Φ , ε_1 and ε_2 on the basis of relations (13).

EXEMPLARY CALCULATION OF THE ROLL DAMPING COEFFICIENT

The exemplary calculations of the nonlinear roll damping coefficient, based on model tests, were performed for a passenger ferry model [2],[3].

Data of the model :

- length between perpendiculars L_{bp} = 3.18 m
- breadth B = 0.56 m
- draught D = 0.12 m
- moulded depth H = 0.28 m
- volumetric displacement V = 132 dm^3

The roll damping coefficient was determined - as an example- -for two states of the hull.: an intact state and a damage state. The damage state was realized by cutting a hole in the ship's side, a midships, over the whole depth of the side. Due to this, outboard water could freely enter the hull and flow over the vehicle deck of the ferry model.

Data of the intact state of the model :

- freeboard F_D = 55 mm
- metacentric height h_0 = 68 mm
- position of the centre of gravity z_G = 246 mm
- dimensionless radius of gyration ρ = 0.35

The dependence of the dimensionless damping coefficient on the roll amplitude for the intact state was approximated by the following polynomial :

$$\nu^L_\Phi = 0.010 + 0.0122\ \Phi_A - 0.00024\ \Phi^2_A \tag{19}$$

which is graphically presented in Fig.3:

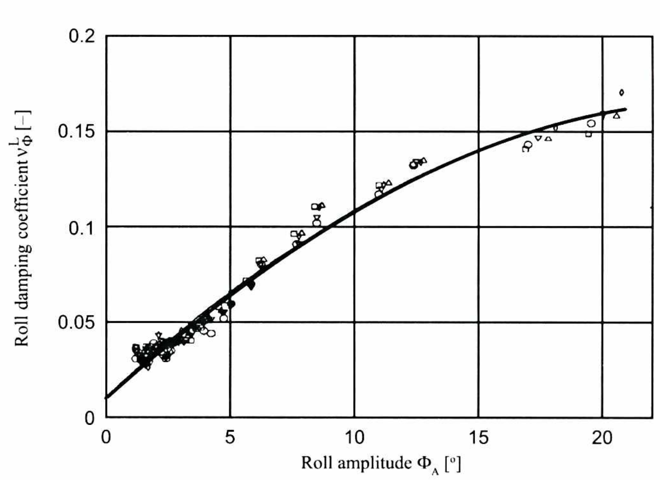

***Fig.3.** Approximation of the dimensionless roll damping coefficient of a passenger ferry model in intact state [3]*

Data of the damage state :

- freeboard F_D = 6 mm
- metacentric height h_0 = 14 mm
- position of the centre of gravity z_G = 252 mm
- dimensionless radius of gyration ρ = 0.39

The dependence of the dimensionless damping coefficient on the roll amplitude for the damage state was approximated by the following polynomial :

$$\nu_\Phi^L = 0.442 + 0.0049\ \Phi_A - 0.00154\ \Phi_A^2 \quad (20)$$

which is illustrated in Fig.4 :

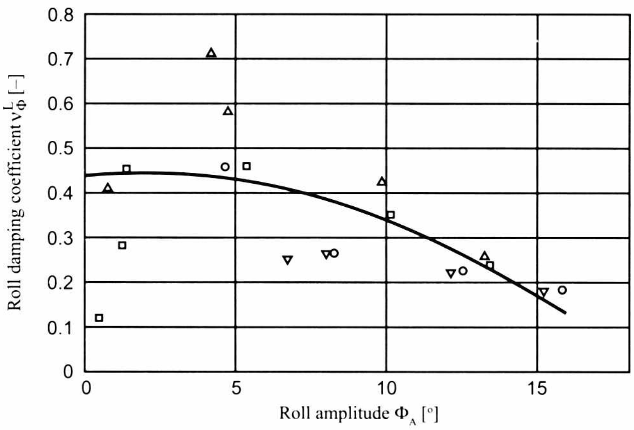

Fig.4. Approximation of the dimensionless roll damping coefficient of a passenger ferry model in damage state [3]

In Fig.3 and 4 the damping coefficients obtained from individual runs for the same loading conditions are marked differently. In Fig.4 a considerable spread of data points can be observed. This is due to the fact that they correspond to the damage conditions. The scatter of the damping coefficient values is caused by the phenomena connected with the water flow into and out of the ship.

SUMMARY AND CONCLUSIONS

- The roll damping coefficient of ship depends on the roll amplitude and this dependence is nonlinear. Hence, for the numerical simulation of ship's movements, the coefficient should be approximated. Model tests are helpful here. In this paper one of the methods for approximating the roll damping coefficient has been presented.

- The exemplary approximation calculations of the roll damping coefficient were conducted for a passenger ferry model in intact and damage states.

- In the intact state the linear part of the damping coefficient ν_Φ = 0.01. The rising character of the dependence of the nonlinear roll damping coefficient on the roll amplitude is rather typical (Fig.3).

- For the damage state, however, the linear part of the damping coefficient is significantly higher : ν_Φ = 0.442. The approximation curve of the nonlinear roll damping coefficient is also different : the coefficient mainly decreases as the roll amplitude increases (Fig.4), which is rather untypical for ships. Such high value of the linear part of the damping coefficient, as well as the course of its approximation curve can be explained by the presence of the water inside the damaged hull of the ship model, that on the vehicle deck in particular.

Appraised by Jan Szantyr, Prof.,D.Sc.,N.A.

NOMENCLATURE

a_0 , a_1 , a_2	– coefficients of the polynomial approximating the nonlinear roll damping coefficient
I_x	– moment of inertia of the hull with respect to x-axis
m_Φ	– inertia moment of roll-added mass
M_L	– equivalent linear roll damping moment (in a short interval)
M_N	– nonlinear roll damping moment
n	– number of measurements of the equivalent linear roll damping moment
t	– time
T_Φ	– roll natural period
α	– roll phase angle
δ_Φ	– linear part of the roll damping coefficient
δ_Φ^L	– equivalent linear roll damping coefficient (in a short interval)
Δ_i	– difference between the equivalent damping coefficient and the i-th measurement of the damping coefficient
ε_1 , ε_2 , ...	– coefficients of the nonlinear part of roll damping
ν_Φ^L	– dimensionless equivalent roll damping coefficient
Φ , $\dot{\Phi}$	– roll angle, roll angular velocity
Φ_A	– roll amplitude
Φ_k , Φ_{k+1}	– successive amplitudes of free decaying roll
ω_Φ	– natural roll frequency

BIBLIOGRAPHY

1. Błocki W.: *Ship Safety in Connection with Parametric Resonance of the Roll.* International Shipbuilding Progress, Vol. 27, No 306, 1980
2. Grzybowski P.: *Roll Damping Measurements, Model M489, Passenger Ferry* (in Polish). Report No RH-98/B-8997, Ship Design and Research Centre. Gdańsk, 1998
3. Grzybowski P.: *Results of Roll Damping Model Tests, Model M489, Passenger Ferry* (in Polish). Report No RH-98/T- 030, Ship Design and Research Centre. Gdańsk, 1998
4. Haddara M.R.: *A Study of the Angle Dependence of Roll Damping Moment.* Ocean Engineering, Vol. 16, No 4, 1989
5. Roberts J.B., Kountzeris A. and Gawthrop P.J.: *Parametric Identification Techniques for Roll Decrement Data.* International Shipbuilding Progress, Vol. 38, No 415, 1991
6. Zhang Y. and Haddara M.R: *Parametric Identification of Nonlinear Roll Motion Using Roll Response.* International Shipbuilding Progress, Vol. 40, No 424, 1993

Miscellanea

TOP KORAB rewards

For several years the Society of Polish Naval Archtects and Marine Engineers KORAB has granted two awards for the best M.Sc. theses from among those commended by the Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology.

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Geometrical modelling of ship hull form by means of the TRIBON / INITIAL DESIGN computer software

The project was elaborated under supervision of Mr. Bogusław Oleksiewicz, D.Sc., the Department of Designing Ships and Ocean Engineering Objects.

Mr Radosław Głodowski, M.Sc. for the project on :
Determination of ship maneouvrability characteristics by means of model testing applied to a fast merchant ship driven by pod azimuthal propellers, as an example

The project was elaborated under supervision of Mr. Wojciech Misiąg, D.Sc., Ship Hydromechanics Department.