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Hydrodynamic moments due to water on ship deck

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An analysis of the ship stability requires computer simulations of the ship motions leading to its capsizing. The large amplitudes of roll motion of the ship are connected with phenomena of immersing of ship deck into water. These phenomena require to take into account additional moments connected with water on a deck. The paper presents a new method (1994) of calculating these additional moments. An approximate and simple calculation of the additional moments is based on the second principle of dynamics applied to an element of a water running off the deck. The additional moments applied in numerical simulations of the ship motions, change significantly the roll motion. The paper presents results obtained from computer simulations. Some of the results are compared with the results of an experiment done with the ship model.

1. INTRODUCTION

The problem presented in this paper is connected with the ship stability safety. Analysis of the mechanism of the ship capsizing and the risk assessment requires computer simulations of the ship motions leading to its capsizing [4, 5]. The roll motion of the ship becomes large when the ship is about to capsize. The large amplitudes of roll motions are connected with the phenomenon of immersing of the ship deck edge into a water. The model tests show that the return roll motion slows down rapidly when water runs off the deck [7]. Substantial additional moments are associated with this phenomenon. These moments cannot be omitted in computer simulations of the ship motions.

There is no paper presenting a method of computing these substantial additional moments connected with the phenomenon of the water running-off the ship deck. There are few papers dealing with so called green water, that is water on the ship deck. Some of them, like [1, 8, 10, 12, 14] consider the phenomenon of liquid sloshing on the deck between bulwarks or sloshing inside the ship compartment [2, 3, 15]. Others, like [11, 16, 17, 18] examine the sloshing of a water into the damaged ship. All these papers do not refer to an event of the water running-off the ship deck. The paper presents a new method of calculating the additional moments acting on the ship deck.

2. HYDRODYNAMIC PHENOMENA CONNECTED WITH IMMERSING OF THE DECK EDGE INTO WATER

The hydrodynamic phenomena connected with immersing of the deck edge into water are schematically presented in Fig. 1. The roll motion with large amplitudes could be divided into two phases. During the first part of the motion the deck edge immerses and the water flows on the deck (b). The ship reaches a maximum roll angle (c) and then begins the return roll motion. The water runs off the deck (d). In this phase the roll motion slows down which was observed experimentally [4], Fig. 4. Slowing down of the roll motion is connected with large additional moments.

I assume that no additional moments act during phase (b) — Fig. 1. The situation dramatically changes at the moment corresponding to point (c). The water running off the deck in phase (d) is separated on the deck edge and the return roll motion is slowed down. It requires to take into account additional moments connected with the water on the deck.

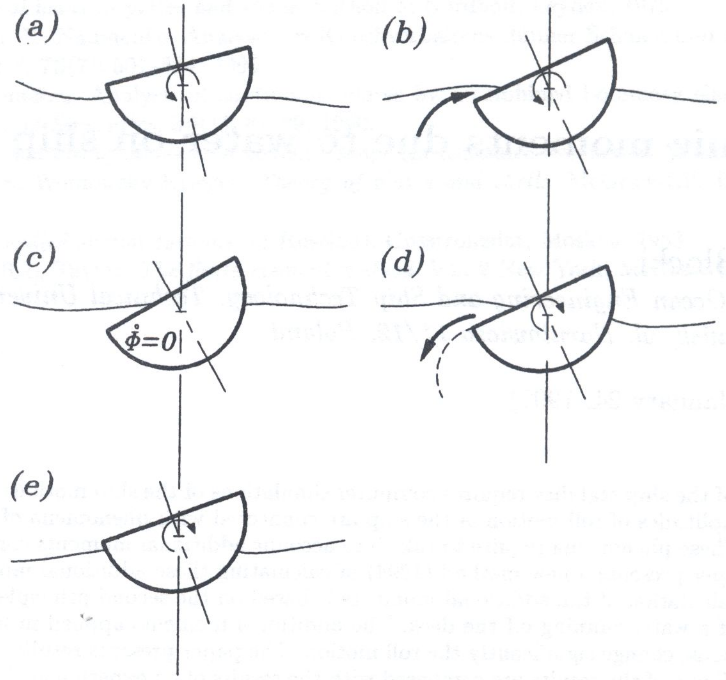

Fig. 1. Phenomena connected with immersing of the ship deck edge.

3. APPROXIMATE FORMULAE FOR ADDITIONAL MOMENTS DUE TO WATER ON THE SHIP DECK

An approximate calculation of the moments acting during the water running off the deck in phase (d) is explained in Fig. 2 and Fig. 3. The mass of this water flowing in time $\mathrm{d}t$ (Fig. 2) is: $\mathrm{d}m = \rho A v \mathrm{d}t$. Taking into account that $v_n = v\cos\Theta$ and that $A = \mathrm{d}A\cos\Theta$ (Fig. 3) we get the intensity of flow of the water:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \rho v A = \rho v_n \mathrm{d}A \tag{1}$$

The second principle of dynamics is applied in the direction $\bar{\mathbf{n}}$ for an element of the water running off the deck [6, 13]:

$$\frac{\mathrm{d}}{\mathrm{d}t}(m v_n) = R_n \tag{2}$$

which can be rewritten as:

$$\frac{\mathrm{d}m}{\mathrm{d}t} v_n + m\frac{\mathrm{d}v_n}{\mathrm{d}t} = R_n\,, \tag{3}$$

where R_n is the force acting on the deck.

Taking into account that $v = r\dot{\Phi}$, $v_n = v\cos\Theta$, $v_n = r\dot{\Phi}\cos\Theta = y\dot{\Phi}$, and $\dfrac{\mathrm{d}v_n}{\mathrm{d}t} = y\ddot{\Phi}$, (see Fig. 3), Eq. (3) can be rewritten as:

$$R_n = \rho\dot{\Phi}^2 y^2 \mathrm{d}A + \rho\ddot{\Phi} y\,\mathrm{d}V \tag{4}$$

and for the element of the moment:

$$\mathrm{d}M = \rho\dot{\Phi}^2 y^3 \mathrm{d}A + \rho\ddot{\Phi} y^2 \mathrm{d}V\,. \tag{5}$$

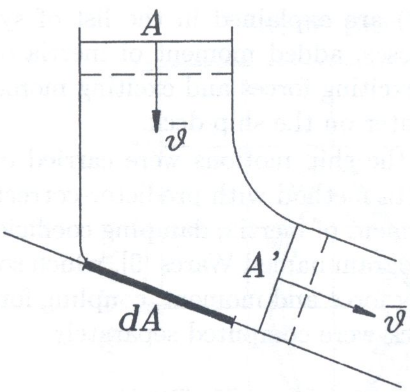

Fig. 2. The water running off the deck above the element dA.

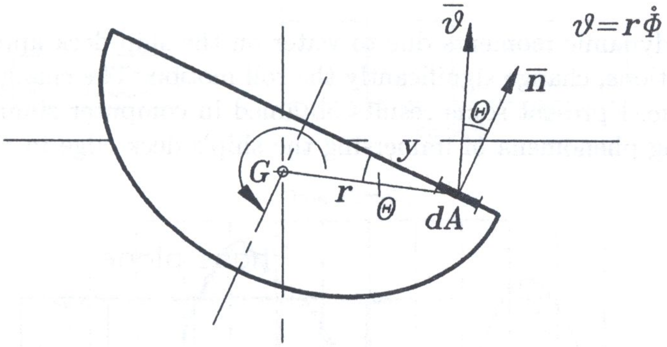

Fig. 3. Relations between the element of the deck area dA, the normal vector to the deck $\bar{n}$ and the velocity $\bar{v}$ of the element of deck area.

The additional moment connected with the water running off the deck may be obtained after integration:

$$M = \dot{\Phi}^2 \rho \int_A y^3 \mathrm{d}A + \ddot{\Phi} \rho \int_V y^2 \mathrm{d}V \,. \tag{6}$$

The first integral is taken over the area of the wetted deck A and the second one over the volume of the water on the deck V. Formula (6) is the sum of two parts: damping moment and added mass moment of the roll:

$$M = I_3 \dot{\Phi}^2 + i_X \ddot{\Phi} \,, \tag{7}$$

where I_3 is the third order moment of the wetted deck area A and i_X is the moment of inertia of the water on the deck with respect to the central axis of the ship.

4. SIMULATIONS OF SHIP MOTIONS WITH IMMERSING OF THE DECK EDGE INTO A WATER

I assume that the following system of coupled, differential and non-linear equations describes sway, heave and roll motions of the ship [4, 5, 6, 13]:

$$\begin{cases} (m_s + m_y)\ddot{y} + 2\delta_y \dot{y} + m_{y\Phi}\ddot{\Phi} + \delta_{y\Phi}\dot{\Phi} = f_y \sin(\omega_e t + \lambda_y) \\ (m_s + m_z)\ddot{z} + 2\delta_z \dot{z} + \rho g A_{\mathrm{w}} z = f_z \sin(\omega_e t + \lambda_z) \\ (I_X + m_\Phi + i_X)\ddot{\Phi} + 2\delta_\Phi \left(1 + \dfrac{e_1}{\omega_\Phi^2} + \ldots\right)\dot{\Phi} + \rho I_3 \dot{\Phi}^2 \operatorname{sign}\dot{\Phi} + \rho g V h_0 (1 + \varepsilon_1 \Phi^2 + \ldots)\Phi \\ \qquad + K_{\Phi z}\Phi z + a_{\Phi z}\Phi z^2 + m_{\Phi z}\ddot{y} + \delta_{\Phi y}\dot{y} = f_\Phi \sin(\omega_e t + \lambda_\Phi) \end{cases} \tag{8}$$

Symbols used in equations (8) are explained in the list of symbols at the end of this paper. Equations (8) include added masses, added moment of inertia of the ship, damping coefficients, restoring force and its moment, exciting forces and exciting moment, coupling forces and coupling moments and moments due to water on the ship deck.

The computer simulations of the ship motions were carried out on the basis of the equations (8). The fourth order Runge–Kutta method with predictor-corrector was used in solving equations (8). Added masses and added moment of inertia, damping coefficients, exciting forces and moment, were taken from the computer program named Wares [9], which solves the radiation and diffraction hydrodynamic problem. Restoring force and moment, coupling forces and moments of the ship and moments due to water on the deck were computed separately.

5. COMPARISON OF EXPERIMENTAL DATA WITH NUMERICAL SIMULATIONS

The additional hydrodynamic moments due to water on the ship deck applied in numerical simulations of the ship motions, change significantly the roll motion. The change could be both in time and in the phase plane. I present some results obtained in computer simulations of the parametric resonance including phenomena of immersing the ship's deck edge in Fig. 4 and Fig. 5. These

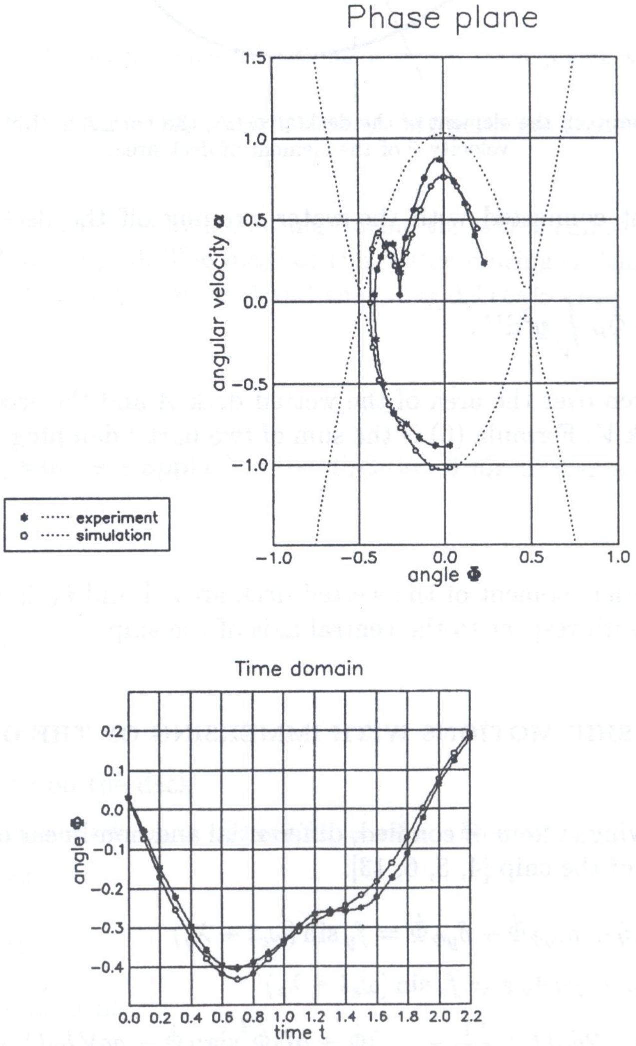

Fig. 4. A fragment of experimental and computer simulation runs of a cylindrical framelike ship's model with the slowing down roll motion connected with the water running off the deck.

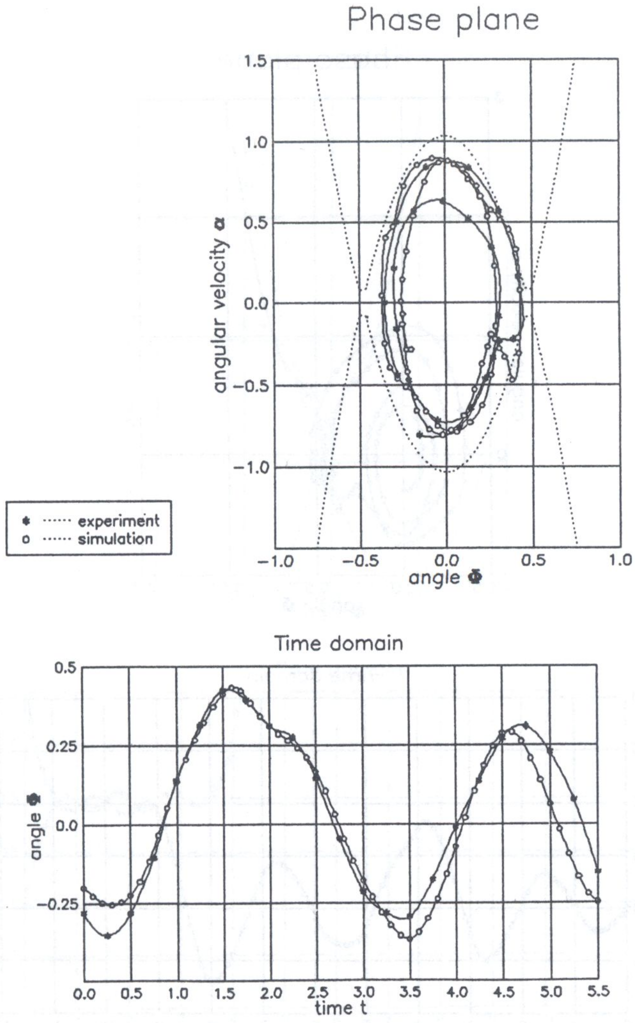

Fig. 5. Experimental and computer simulation runs of a cylindrical framelike ship's model with the slowing down roll motion connected with the water running off the deck.

results are compared with the experimental ones for a cylindrical framelike ship model. Results of the computer simulations agree fairly well with experiment.

6. PSEUDOSTATIC ROLL ANGLE

Some descriptions of capsizing ship models, particularly in beam sea, contain so called pseudostatic roll angle. The ship model reaches this angle before capsizing. Motions with pseudostatic roll angle mean that the model sways and heaves but it does not roll (the roll angle is almost constant). Pseudostatic roll angle is bigger than the angle of immersing the deck edge and smaller than the angle at which the righting moment vanishes. The cause of appearing this almost constant roll angle was not clear. The opinion was that that existence of the bulwark is the reason for pseudostatic roll angle.

Observations of some experimental and numerical simulations of capsizing of the ship models reveal that the reason of pseudostatic roll angle is the nature of additional hydrodynamic moments due to water on the ship deck. Simulations were carried out without bulwark and ship model many times reached the pseudostatic roll angle before capsizing. Such situation is shown in Fig. 6 and Fig. 7. One can see that the ship model performs regular heave motion (figure at the bottom — displacement) and it rolls with almost constant angle (figure in the middle — angle).

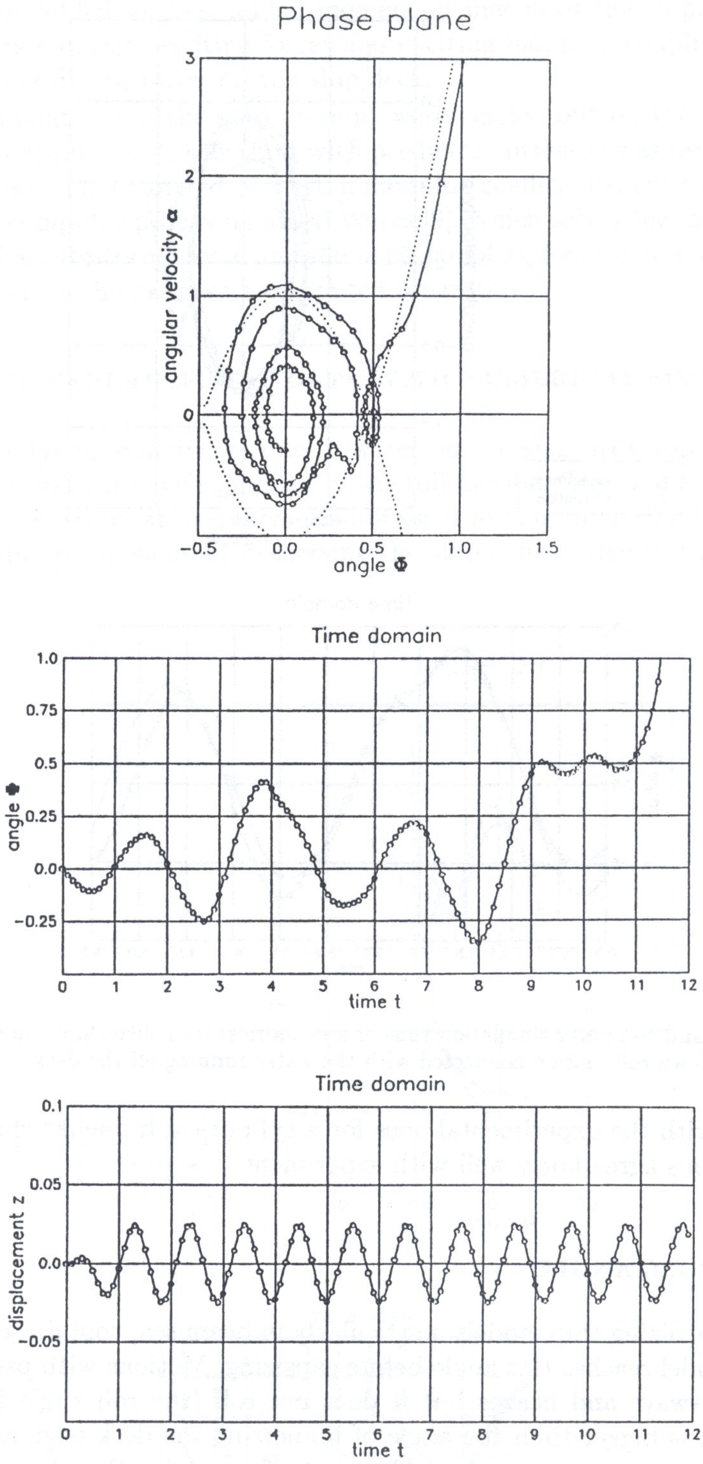

Fig. 6. Computer simulation run of capsizing of a cylindrical framelike ship's model with appearing of the pseudostatic roll angle.

7. CONCLUSIONS

The substantial additional hydrodynamic moments due to water running-off the ship deck are composed of two parts: damping moment and added mass moment, as is expressed by formula (6).

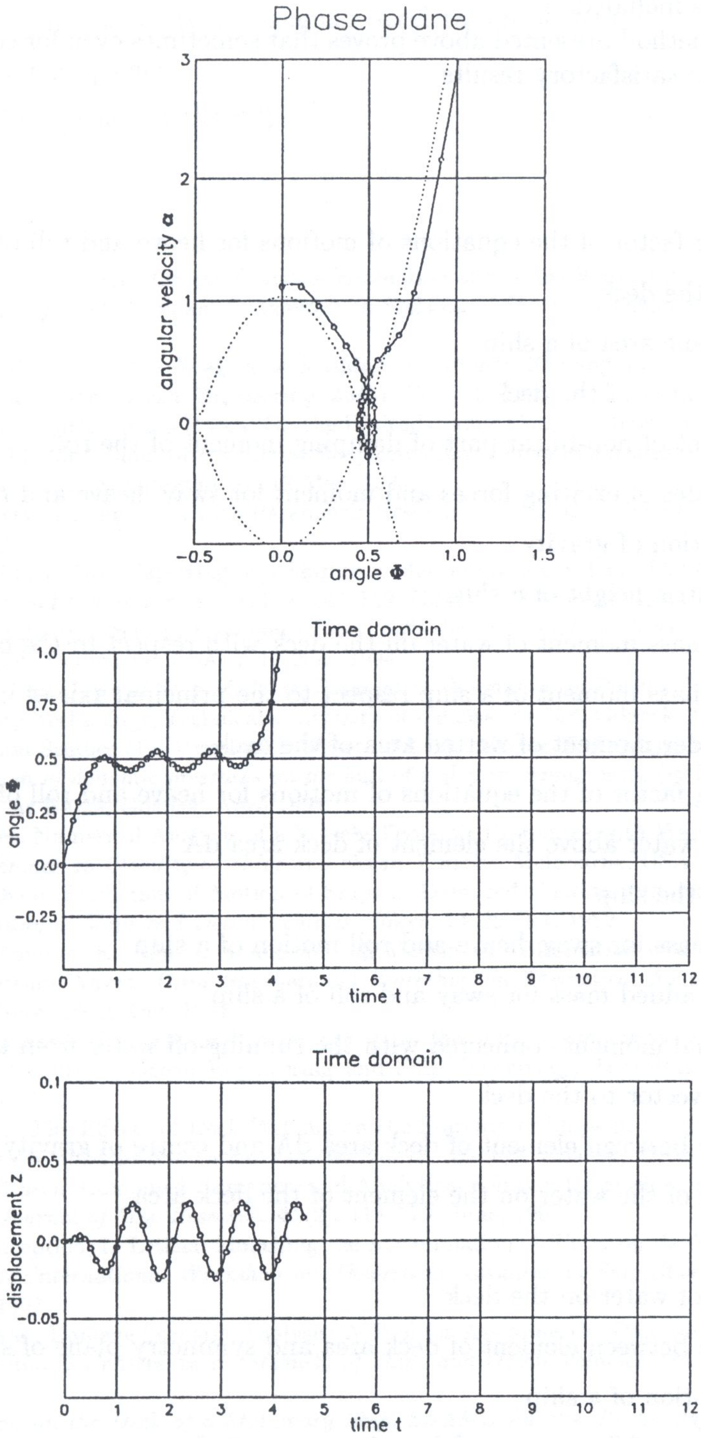

Fig. 7. Computer simulation run of capsizing of a cylindrical framelike ship's model with appearing of the pseudostatic roll angle.

The former is calculated by integration over the wetted deck area, whereas the latter by integration over area filled with the water above the deck. These additional moments depend on angular velocity and acceleration of the ship roll. The use of formula (6) in simulation of the ship motions allows to identify the cause of appearing of the so called pseudostatic roll angle. Calculations presented in here could be applied to ships with different shapes of wetted decks (different superstructures) as the third moment is included.

In my opinion the method presented above proves that sometimes even for complicated problems simple methods lead to satisfactory results.

LIST OF SYMBOLS

$a_{\Phi z}$	coupling factor of the equations of motions for heave and roll of a ship
A	area of the deck
A_{w}	waterplane area of a ship
$\mathrm{d}\mathbf{A}$	element area of the deck
e_1	coefficient of non-linear part of damping moment of the roll
f_y,f_z,f_Φ	amplitudes of exciting forces and moment for sway, heave and roll of a ship
g	acceleration of gravity
h_0	metacentric height of a ship
i_X	inertia mass moment of water on the deck with respect to the central axis of a ship
I_X	inertia mass moment of a ship respect to the principal axis of inertia
I_3	third order moment of wetted area of the deck
$K_{\Phi z}$	coupling factor of the equations of motions for heave and roll of a ship
m	mass of water above the element of deck area dA
m_s	mass of the ship
m_y, m_z, m_Φ	added mass for sway, heave and roll motion of a ship
$m_{y\Phi}, m_{\Phi y}$	coupled added mass for sway and roll of a ship
M	additional moment connected with the running-off water from the deck
$\bar{\mathbf{n}}$	normal vector to the deck
r	distance between element of deck area dA and centre of gravity of ship G
R_n	reaction of the water on the element of the deck area
t	time
V	volume of water on the deck
y	distance between element of deck area and symmetry plane of ship
y	sway motion of a ship
$\delta_y, \delta_z, \delta_\Phi$	coefficients of linear part of damping moments for sway, heave and roll
$\delta_{y\Phi}, \delta_{\Phi y}$	coefficients of coupled damping moments for sway and roll
ε_1	coefficient of non-linear part of restoring moment of the roll
Θ	angle between two vectors: velocity $\bar{v}$ and direction $\bar{\mathbf{n}}$ (Fig. 3)
$\lambda_y, \lambda_z, \lambda_\Phi$	phase angles between excitation forces and moment for sway, heave, roll
ρ	density of water
v	velocity of the element of deck area dA

v_n	projection of the velocity $\bar{v}$ on the direction $\bar{\mathbf{n}}$
$\Phi, \dot{\Phi}, \ddot{\Phi}$	angle, angular velocity and angular acceleration of the roll
ω_e	encounter frequency
ω_Φ	natural frequency of the roll

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