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INFLUENCE OF WEATHER CONDITIONS ON THE SHIP'S SAFETY DURING REPLACEMENT OF BALLAST WATER

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Abstract

The sequential method of ballast water replacement at sea during the ship voyage is commonly used on board the ships. However, the successive emptying and filling of ballast tanks causes the occurrence of hazards to ship's safety. The article presents the calculation results of ship roll motions, pitch motions, slamming and emergence of propeller during ballast replacement at different sea states. It has been shown at which stages of ballast replacement specific hazards arise and how they could be avoided or minimized, especially under severe weather conditions.

Key words: *ship ballasting, ship's safety during replacement of ballasts, sequential method*

1. Introduction

The article [2] presents the calculation results of the m/v „Orla"ship service parameters when applying the sequential method of the replacement of ballasts during the ship's voyage at sea. For certain steps of emptying and filling of ballast tanks on calm water the service parameters values were higher than criterial values and this fact already constituted a hazard to safety of the ship. In this article certain sea-keeping abilities of the ship shall be presented which are of major significance during replacement of ballasts, mainly for these cases in which hazard to ship safety occurred already on calm water.

2. Ship's sea-keeping abilities during replacement of ballasts

For estimating the ship's safety on waves during the operation of replacement of ballasts the following sea-keeping abilities were chosen which may constitute a hazard to safety of the ship [4]:

- rolling,
- pitching,
- slamming,
- emergence of propeller,

2.1. Ship motions on waves

Using the commonly applied linear theory of ship motions [3], within the scope of which, on regular waves described by equation:

$\zeta(t) = \zeta_A \cos(kx - \omega t)$,(1)ship motions on these waves are given in the following form:

$$u = u_A \cos(-\omega_E t + \varepsilon_u), \tag{2}$$

where:

ζ_A – amplitude of regular wave,

k – wave number,

$$k = \frac{\omega^2}{g} \tag{3}$$

ω – frequency of regular wave,

u_A – frequency transfer functions of ship motions „u", (for $u = 4$ - rolling Φ, $u = 5$ - pitching θ, respectively),

ω_E – frequency of encounter of ship motions,

$$\omega_E = \omega - kV \cos\beta_w \tag{4}$$

V – ship speed,

β_W – wave direction related to ship ($\beta_W = 0^\circ$ following sea [waves] from the aft, $\beta_W = 90^\circ$ beam sea [lateral wave], $\beta_W = 180^\circ$ head sea).

ε_u – angle of phase displacement between wave and ship motion.

The random motions of the ship on the irregular waves can be simply determined on the basis of knowledge about frequency transfer functions of ship motions on regular waves and about function of the random wave energy spectral density. The variance of ship motions is then equal to:

$$D_{uu}(\beta_W, V) = \int_0^\infty [Y_{u\zeta}(\omega_E / \beta_W, V)]^2 S_{\zeta\zeta}(\omega_E) d\omega_E \, , \tag{5}$$

where:

D_{uu} – variance of motions u,

$Y_{u\zeta}$ – frequency transfer functions of ship motions u on regular waves,

$S_{\zeta\zeta}(\omega_E)$ – function of the random wave energy spectral density, the value of which depends mainly on the significant wave height H_S and on period T_1, The root of a variance D_{uu} is a mean square deviation of ship motions on irregular waves, on the basis of which statistical value of random motions can be calculated, having the assumed probability of exceeding, e.g.:

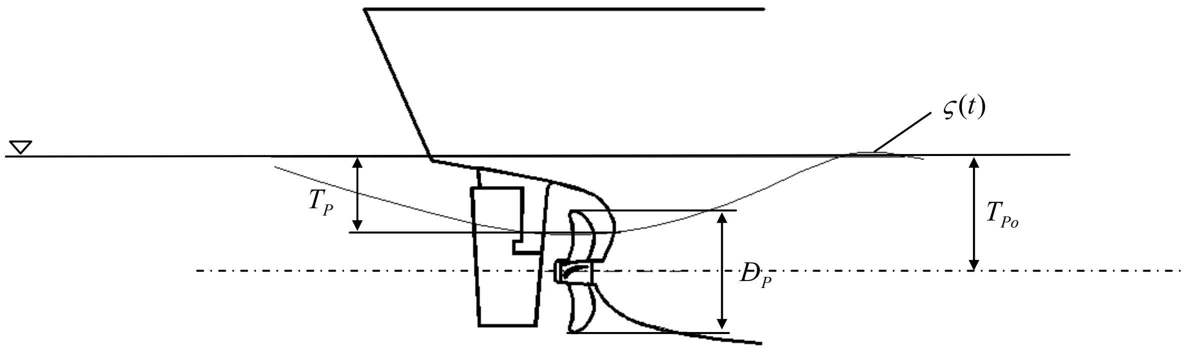
$$\bar{u}_{A1/3} = 2{,}0\sqrt{D_{uu}}\ , \qquad (6)$$

$u_{A1/3}$ – significant amplitude of ship motions u (mean value of motion amplitude u out of 1/3 highest values of motions).

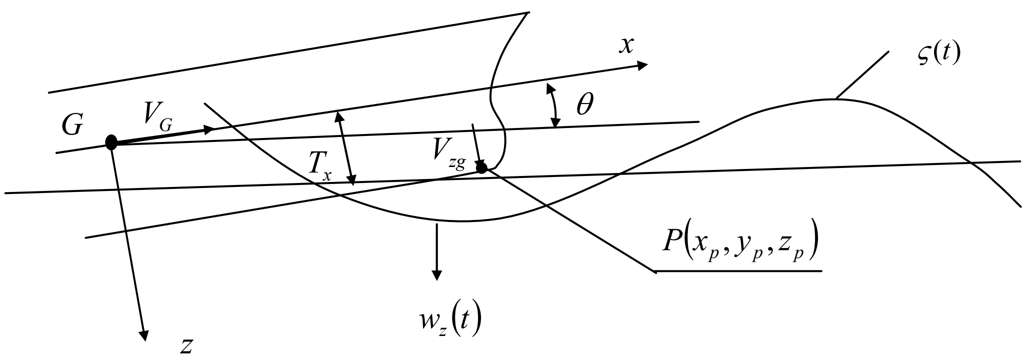
Other aforementioned phenomena, arising during ship navigation on waves, can be made conditional on ship motions.

2.2. Ship relative motions on waves

During ship motions on waves, its movement can be determined, related to wavy water surface. The occurring relative movement has a decisive influence on such phenomena like the emergence of propeller (drg. 1) or slamming (drg. 2, in case of slamming, what is also important is the relative vertical speed of the ship in area in which the probability of slamming occurrence is calculated).



Drg. 1. Influence of relative movement of the ship on emergence of propeller



Drg. 2. Bow emergence and relative velocity of bow submergence in wavy water (slamming)

The vertical relative displacement of the ship resulting from the ship motions and from shape of wavy surface is equal to:

$$R_{ZP} = Z_G + y_P \Phi - x_P \Theta - \zeta(t)\,, \tag{7}$$

where:

$\zeta(t)$ is the wave profile described by equation (1),

Z_G – ship heaving.

The vertical component of relative velocity of bow submergence in water (drg. 2) is equal to:

$$V_{RZP} = \dot{Z}_G + y_P \dot{\Phi} - x_P \dot{\Theta} - V\,\Theta - w_Z(t)\,, \tag{8}$$

where:

$\dot{Z}_G, \dot{\Phi}, \dot{\theta}$ – speeds of ship motions heaving, roll motions and pitching,

$w_z(t)$ – is the vertical component of water particle velocity in the wave motion,

x_P, y_P – coordinates of point, for which relative movement or relative velocity is calculated, (in this case it will be respectively the point lying on the propeller blade – drg. 1, or on the bottom in the bow area – drg. 2).

Considering the fact that emergence of propeller or slamming are not continuous phenomena and they occur only in certain [specific] situations, for these phenomena probability is calculated when:

- the relative motion exceeds the depth of the propeller T_P point position (for the emergence of propeller, drg. 2),
- the relative motion exceeds the bow draught T_x and at the same time the relative velocity of bow submergence in water V_{RZP}, drg. 1, shall exceed the critical velocity $V_{kr} = 0{,}093\sqrt{gL}$ (for slamming).

For the phenomena listed hereinabove their number and probability of their occurrence are as follows:

– for the emergence of propeller:

$$N_{ZP} = \frac{3600 \cdot p_{ZP}}{T_u}, \tag{9}$$

where:

N_{ZP} – number of bow emergences within an hour,

$\overline{T}_u$ – mean period of motions,

p_{ZP} – probability of the emergence of propeller:

$$p_{ZP} = \exp\left(-\frac{H_{EZP}^2}{2c_u D_{ZP}}\right), \tag{10}$$

D_{ZP} – variance of relative water motions at the ship's side, in the propeller area,

c_u – correction factor considering inaccuracy of linear model of ship motions on real wave, [6],

H_{EZP} – effective propeller immersion draught, including height of wave produced by ship movement with speed V ,

– for slamming:

$$N_{SL} = \frac{3600 \cdot p_{SL}}{T_u}, \tag{11}$$

where:

N_{SL} – number of bow emergences within an hour,

p_{SL} – probability of bow emergence and critical velocity exceeding,

$$p_{SL} = \exp\left(-\frac{T_{EXSL}^2}{2c_u D_{SLW}} - \frac{V_{KRSL} 2}{2c_u D_{SLP}} \right), \tag{12}$$

T_{EXSL} – effective ship draught in area for which probability of bow emergence is calculated, including height of wave produced by ship movement with speed V ,

D_{SLW} – variance of bow relative motions,

V_{KRSL} – critical velocity of bow submergence in water, for which probability of deck wetness is calculated,

D_{SLP} – variance of bow relative velocity.

2.3. Criteria of ship seakeeping ability estimation

On the basis of many-years' observations and experience, permissible values of ship motions and of accompanying phenomena have been specified; when these are exceeded, it may endanger safety of the ship, of the crew or of the equipment working on the ship, thus resulting in limitation of transport mission. Level of permissible values depends also on ship type and size. Specification of criteria, proposed by different researchers for selected seakeeping abilities is included in [5], [6].

For estimating the ship's safety during the operation of replacement of ballasts in waves conditions the following criterial values are assumed:

- for ship roll motions – $\Phi_{A1/3} = 12^\circ$
- for pitch motions – $\theta_{A1/3} = 3^\circ$
- for slamming – $N_{SL} = 20{,}3$ times/hour
- for the emergence of propeller – $N_{ZP} = 250$ times/hour

When investigating the influence of the ship's speed and ship's course related to [direction of] waves, the additional intermediate criteria were assumed:

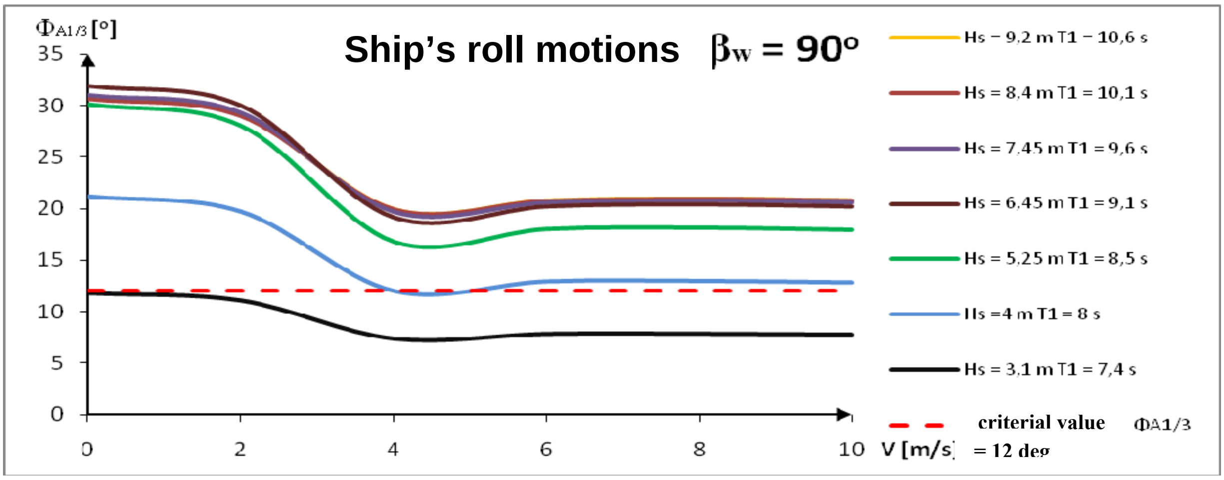
- for ship roll motions – $(\Phi_{A1/3})_1 = 10^\circ$ i $(\Phi_{A1/3})_2 = 12^\circ$
- for pitch motions – $(\theta_{A1/3})_1 = 2^\circ$ i $(\theta_{A1/3})_2 = 3^\circ$

– for slamming – $(N_{SL})_1 = 15$ times/hour and $(N_{SL})_2 = 20{,}3$ times/hour

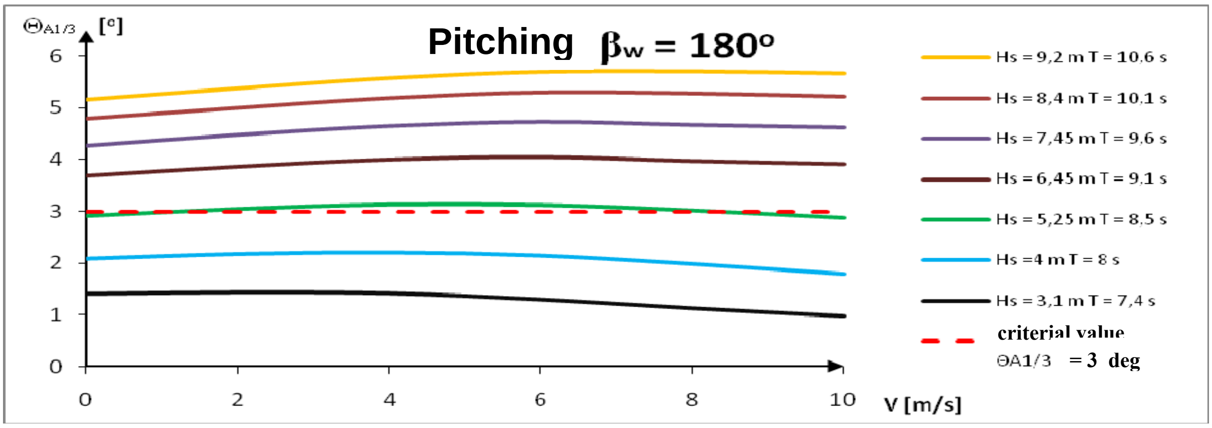
– for the emergence of propeller – $(N_{ZP})_1 = 200$ times/hour and $(N_{ZP})_2 = 250$ times/hour

3. Results of calculations of the selected ship's sea-keeping abilities during replacement of ballasts at sea

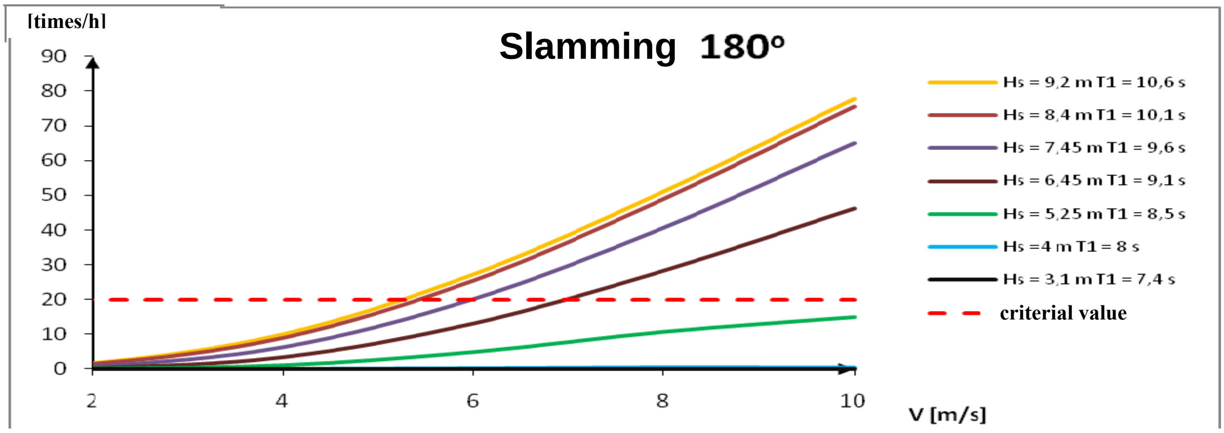
Calculations of the aforementioned seakeeping abilities have been performed for different sea states, specified by the significant wave height H_S and period T_1 (values of these parameters have been assumed for navigation line (ocean route) passing through the Northern Atlantic), for particular steps of ballast replacement, and at the same time for each step the calculations have been performed for a different state [percentage] of the ballast tank filling from 100% (full tank) to 0% (empty tank) every 25%. The exemplary calculation results for selected steps of ballast replacement are presented in drg 3 ÷ 6 (full set of calculations is included in [1]).



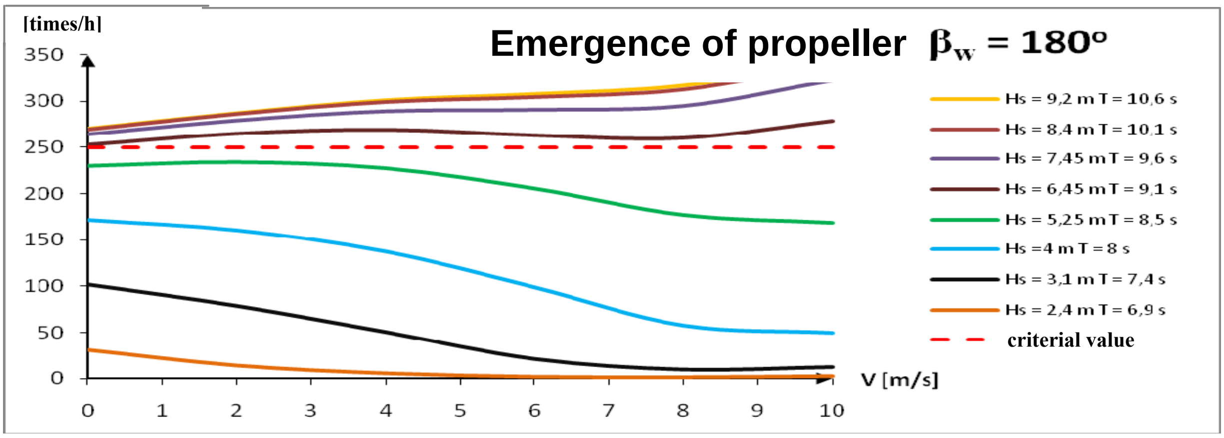
Drg. 3. Influence of sea state on significant value of ship's roll motions. Step "1" – state [percentage] of tank/tanks filling 50%



Drg. 4. Influence of sea state on significant value of ship's pitch motions. Step "1" – state [percentage] of tank/tanks filling 50%

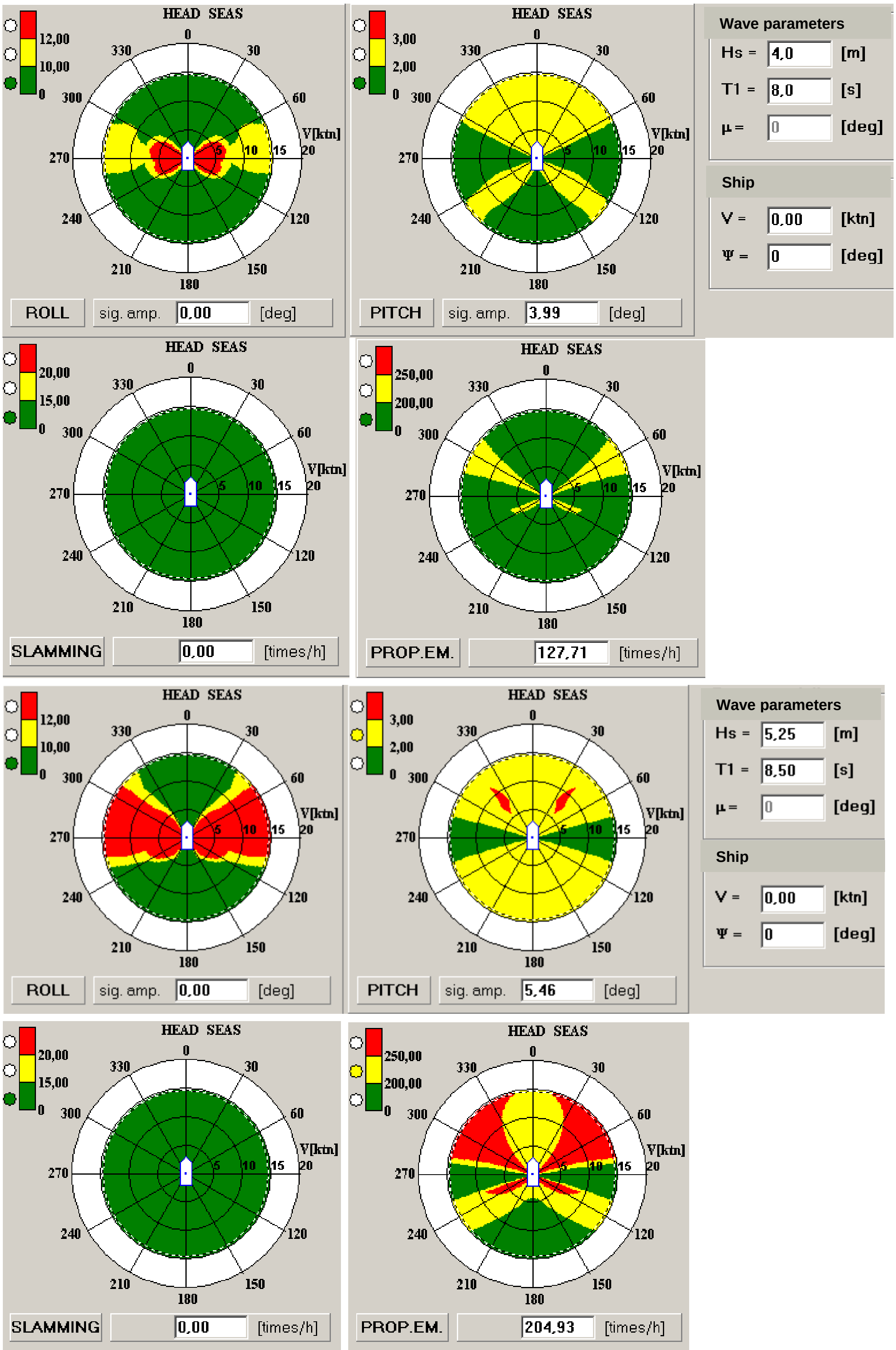


Drg. 5. Influence of sea state on frequency of flamming occurrence. Step "1" – state [percentage] of tank/tanks filling 50%



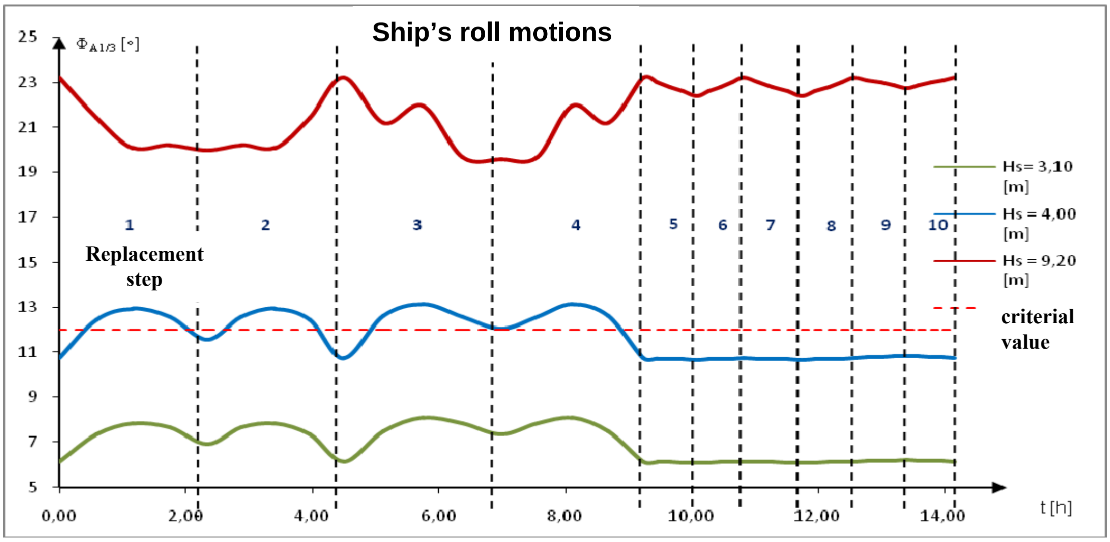
Drg. 6. Influence of sea state on frequency of emergence of propeller. Step "1" – state [percentage] of tank/tanks filling 50%

Drawing 7 presents the influence of the ship's speed and ship's course related to direction of waves on selected seakeeping abilities for different sea states. The following states are presented in this drawing: safe ballast replacement (green colour), warning (yellow colour) and hazard (upper/maximum criterion exceeded – red colour). This drawing shows that at severe weather conditions, in order to limit the hazard state at ballast replacement, the ship's course related to wave direction can be reduced and/or changed.

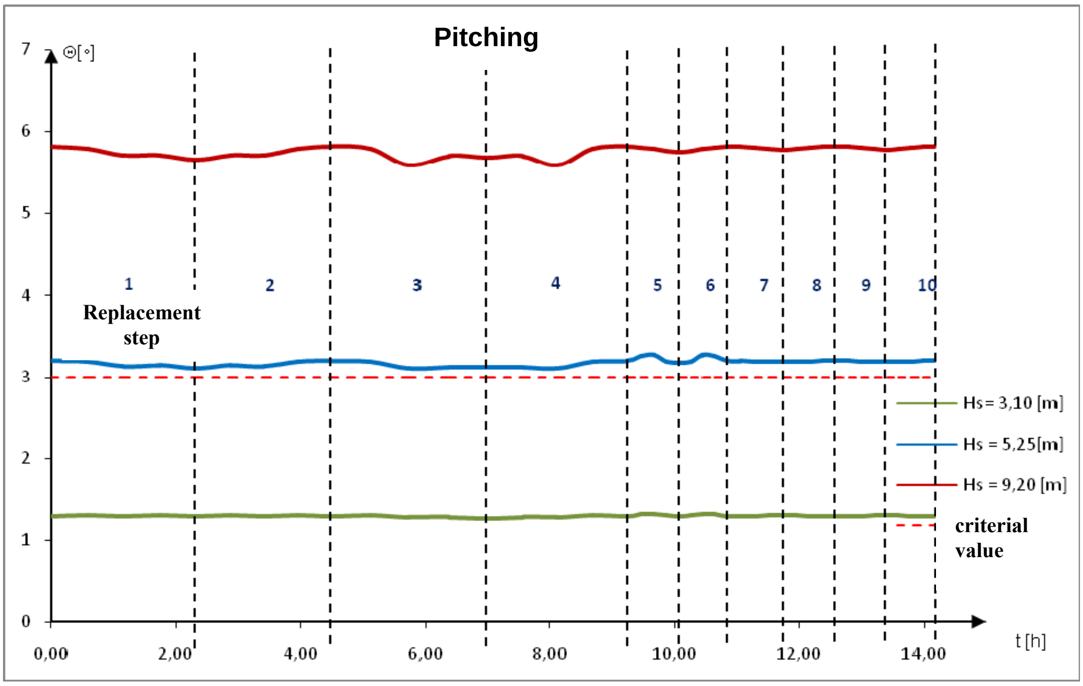


Drg. 7. The influence of the ship's speed and ship's course related to direction of waves on selected seakeeping abilities. Step "1" – state [percentage] of tank/tanks filling 50%

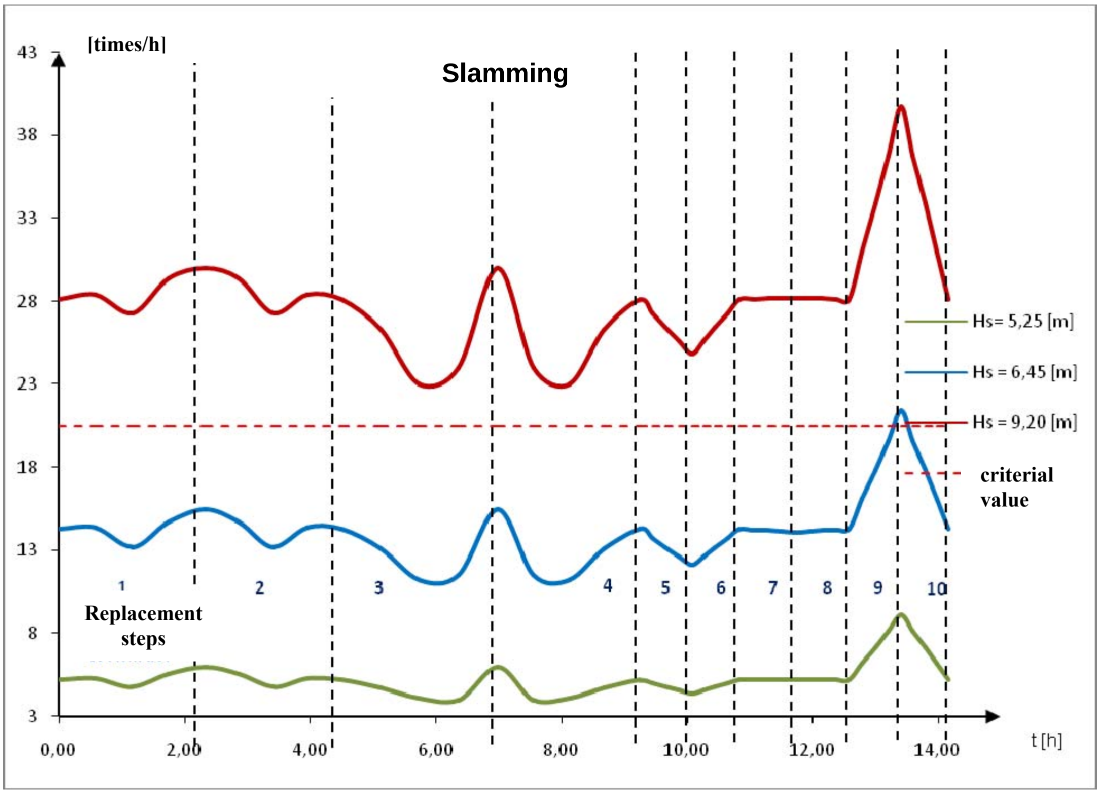
The calculated values of seakeeping abilities for the whole process of ballast replacement are presented in drgs 8 ÷ 11, for different sea states and ship service speeds.



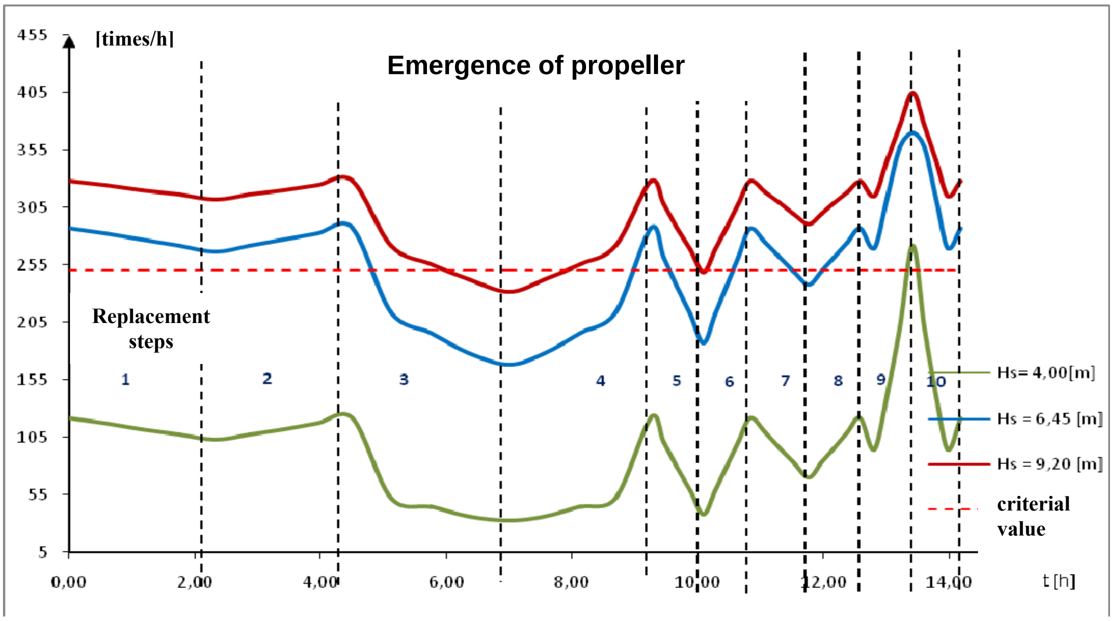
Drg. 8. The ship's roll motions on waves ($\beta_w = 90^\circ$)during the ballast water replacement on the m/v „Orla" ship



Drg. 9. The ship's pitch motions on waves ($\beta_w = 180^\circ$)during the ballast water replacement on the m/v „Orla" ship



Drg. 10. Slamming ($\beta_w = 180^\circ$) during the ballast water replacement on the m/v „Orla" ship



Drg. 11. The propeller emergences on waves ($\beta_w = 180^\circ$)during the ballast water replacement on the m/v „Orla" ship

4. Conclusions from the conducted tests and investigations

The obtained results in form of changes of the values of the investigated seakeeping abilities and possible exceeding of criterial values for particular steps of ballast replacement fully comply with results of analyses for calm water [2]. With the increase of sea state (wave height) the criterial values are exceeded more and more frequently. So it is possible to determine the maximum weather conditions in which the operation of ballast replacement can be carried out safely. Another option is the instantaneous reduction of the ship speed and/or the change of the ship course for the stage (step) of the ballast replacement for which the exceeding of criterial values occurred. It is also possible to change the sequence of emptying and filling of ballast tanks so as to minimize the hazard arising at a given sea state (such situations were investigated in [1])

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