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Modelling of green water ingress into holds of an open-top containership in its preliminary design phase

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ABSTRACT

In this paper a method is presented of modelling the green water ingress into holds of open-top containership, which can be useful in the preliminary ship design phase. As a result of the research a mathematical formula which makes it possible to determine a minimum freeboard height with a view of as- low- as- possible occurrence rate of green water ingress into holds at given ship design parameters, was obtained. The research was carried out under assumption of constant ship hull dimensions. The design formula was elaborated by using a method based on a goal-oriented conceptual approach to formulation of design criteria, proposed by IMO. On the basis of the concept a deterministic scenario describing operational conditions of the ship in question, was assumed, and for the conditions the research was performed.

Keywords: green water ingress into ship holds, goal-oriented stability standards, modelling, open-top containership, preliminary designing, ship hull

INTRODUCTION

The traditional design process of ships develops in an iterative way in accordance with the so-called Evans or Andrews-Evans spiral where design characteristics are evolutionarily improved by making successive trial – error steps. Knowledge about a designed ship in preliminary design phase is slight as several technical ship parameters depend on data which are not available in this phase of designing. In order to increase degree of accuracy of the preliminary design phase the designers must be fitted with appropriate tools for precise prediction of selected design characteristics in this design phase, based on ship's main design parameters.

One of the main design problems of open-top containerships is green water entering the deck resulting in water ingress into the holds. As this type of ships does not comply with the requirements of the Load Line Convention, Maritime Administration may admit the ship to service at sea provided that aditional model tests described in [6] would be performed (the test conditions are described in a further part of the paper).

Amount of water ingress into the holds of open-top containership depends a.o. on: wave parameters, ship motion parameters, ship hydromechanical and geometrical parameters such as: form and dimensions of underwater part of ship's hull (especially ship length), draught, form of ship's hull stern and bow part, freeboard height, deck shape as well as bulwark structure [2, 3, 13].

Number of geometrical parameters which influence the phenomenon of water ingress into the holds is large, hence in order to eliminate unimportant ones the investigations can be carried out in two ways (according to [11]):

★ to change hull dimensions - keeping hull form unchanged (Fig. 1a)
★ to change hull form - keeping hull dimensions unchanged (Fig. 1b).

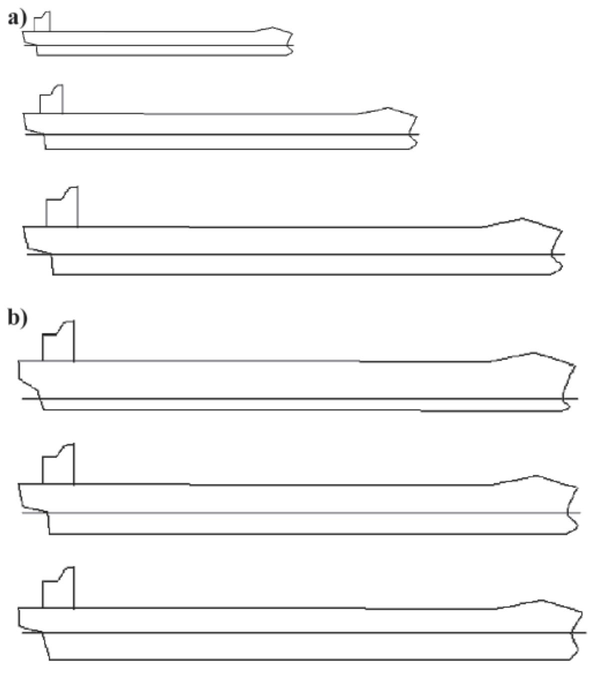

Fig. 1. *Two ways of investigation of influence of hull form and hull dimensions on seakeeping qualities [11].*
a) *unchanged hull form, changeable hull dimensions;*
b) *unchanged hull dimensions, changeable hull form*

Therefore the investigations in question were split in two stages:

- the investigations of influence of ship hull form parameters on green water ingress into the holds at ship hull dimensions kept unchanged
- the investigations of influence of ship hull dimensions on green water ingress into the holds at hull form kept unchanged

In this paper are presented results concerning the first stage of the investigations, i.e. the hull form influence on water ingress into holds at hull dimensions kept unchanged.

The investigations were focused only on:

- influence of form parameters of ship's hull underwater part
- influence of freeboard height (FB)
- influence of initial transverse metacentric height (GM)

out of all parameters influencing the phenomenon of water ingress into the holds.

In compliance with [2, 13] these are the factors most influencing the phenomenon of green water entering the deck, which - in consequence - are capable of influencing water ingress into the holds, to a large extent. And, the initial transverse metacentric height constitutes a parameter which significantly influences ship rolling, that can in turn influence relative ship motion in the deck- side zone, hence also green water entering the deck and holds.

The investigations were performed by applying numerical calculations based on the methods not adjusted to determination of amount of water ingress into the holds (but only of statistical frequency of water entering the deck). From results of the research [1, 5] implies the relations between probability of water entering the deck and amount of water ingress into the holds (Tab. 1). And, the results concerning FPSO ships show the linear relation between the water height on the deck and freeboard height exceedance (Fig. 2) [2, 3]:

$$H0 = a_H \cdot h \qquad (1)$$

where:

H0 – water height on the deck

a_H – a parameter dependent on location of a given point on the deck, and on bow form

h – maximum exceedance of freeboard [3]:

$$h = r - FB \qquad (2)$$

where:

r – relative wave motion (Fig. 3)

FB – freeboard.

Tab. 1. *Water ingress into the holds, where: V_{gw} – hourly volumetric rate of water ingress, p_{dws} – occurrence probability of water entering the deck [1, 5]*

Test no.	V_{gw} [m³/h]	p_{dws} [%]
8057	60	4.3
8058	60	1.6
8063	0	0

Therefore in the presented investigations the linear relationship between occurrence rate of green water entering the deck and amount of water on the deck, was assumed, and the phenomenon of water ingress into the holds was modeled by applying the statistical occurrence rate of green water ingress onto the deck.

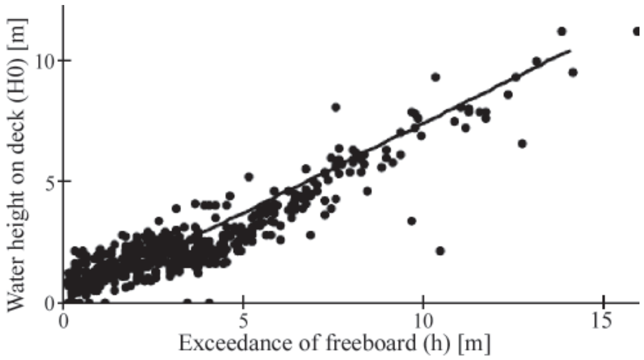

Fig. 2. *Relation between the water height on the deck, H0, and the exceedance of freeboard, h, for a FPSO ship [3]*

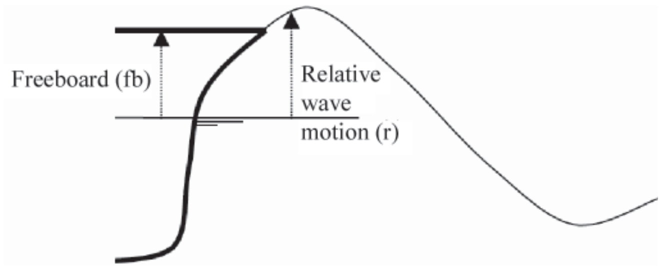

Fig. 3. *Definition of the relative wave motion (r) and freeboard (fb) [3]*

Hence the investigations presented in this paper were aimed at the following:

- determination of how far initial transverse metacentric height influences water ingress into the holds
- determination of which hull form parameters influence significantly water ingress into the holds at the most unfavourable values of initial transverse metacentric height kept constant
- determination of a relation between important hull form parameters, freeboard height and water ingress into the holds
- elaboration of an analytical function which would make it possible to calculate a minimum freeboard height depending on hull form parameters and an assumed occurrence rate of water ingress into the holds.

For the investigations the method shown in Fig. 4 was chosen. In the proposed method it was assumed that the criterion of water ingress into the holds was formulated for the operational conditions complying with [9, 11], assuming an appropriate deterministic scenario. Such approach is in accordance with the conceptual „goal-oriented" approach to formulation design criteria, proposed by the IMO Maritime Safety Committee [9]. As the deterministic scenario (operational conditions) was assumed the following conditions which comply with the IMO recommendations concerning execution of model tests on open-top containerships [6] were selected:

- the recommended significant wave height H_s = 8.5 m
- wave periods taken every 30 s within the range from 3.5 s to 17 s
- the ship motion parameters most unfavourable with a view of green water entering the deck: (the ship speed v and wave encounter angle β)
- full load conditions (i.e. maximum ship draught)
- the investigations were performed for the point on the deck, in which the greatest green water ingress onto the deck occurs (bow part in vicinity of 1st hold).

Preliminary numerical calculations were performed to determine the ship motion parameters most unfavourable with a view of water entering the deck. From the calculations resulted that for the assumed ship hull forms (described in a further part of this paper) the most unfavourable ship motion parameters were the following: the ship speed v = 10 m/s and the wave encounter angle β = 60° (in the reference frame: 0° – following wave, 180° – head wave). As a matter of fact the value of the wave encounter angle β is not in compliance with the research [1], but may be that for such β values the relative motions of underwater part of ship hull are the greatest and cause the largest amount of water to enter the deck.

Ship hull forms obtained by modelling the hull form with the use of the curve of frame section areas, were assumed the model variants.

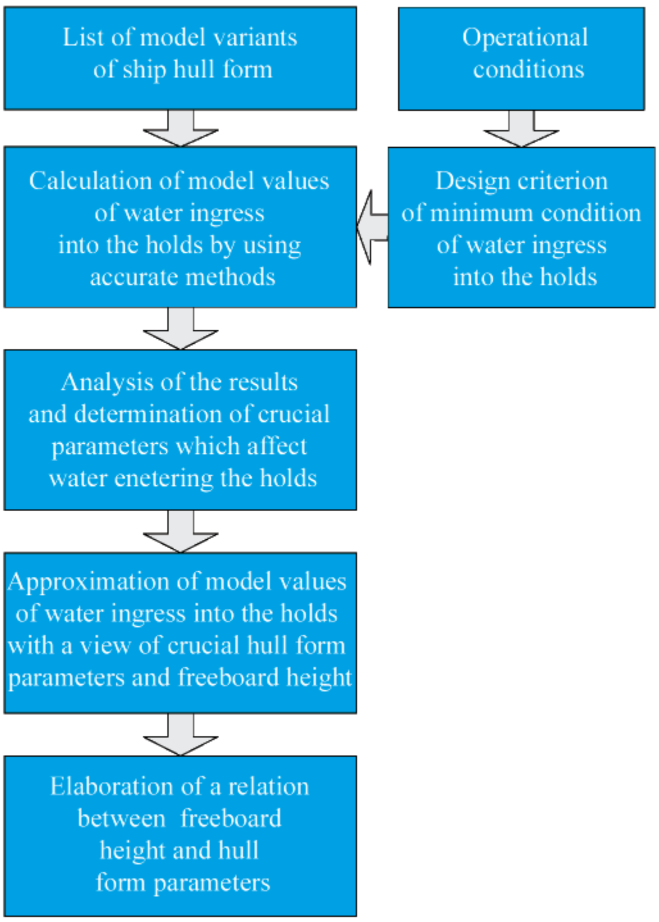

Fig. 4. Schematic diagram of the investigation method

MODELLING SHIP'S HULL FORM BY MEANS OF THE CURVE OF FRAME SECTION AREAS

In the presented investigations ship's hull form was represented by using the curve of frame section areas F(x). The curve was modeled in the same way as presented in [7], i.e. by means of the following analytical functions:

$$F_A = A + Bx + Cx^2 + Dx^3 \quad (3)$$

$$F_F = E + Fx + Gx^2 + Hx^3 \quad (4)$$

where:

F_A – values of the curve of frame section areas of stern part of hull (Fig. 5)
F_F – values of the curve of frame section areas of bow part of hull
x – distance
A, B, C, D, E, F, G, H – constants determined under the following assumptions (acc. [7]):

$$F_A = 0 \text{ for } x = 0 \quad (5)$$

$$dF_A/dx = AS \text{ for } x = 0 \quad (6)$$

$$dF_A/dx = 0 \text{ for } x = L_A \quad (7)$$

$$F_A = F_{max} \text{ for } x = L_A \quad (8)$$

$$dF_F/dx = 0 \text{ for } x = L_{AM} \quad (9)$$

$$F_F = F_{max} \text{ for } x = L_{AM} \quad (10)$$

$$F_F = 0 \text{ for } x = L \quad (11)$$

$$dF_F/dx = FS \text{ for } x = L \quad (12)$$

where:

L – ship length
F_{max} – area of frame section in the midship body zone
L_A – length of stern part of hull
L_{AM} – length of stern part and midship body of hull
AS – slope of the curve F(x) at aft perpendicular
FS – slope of the curve F(x) at fore perpendicular.

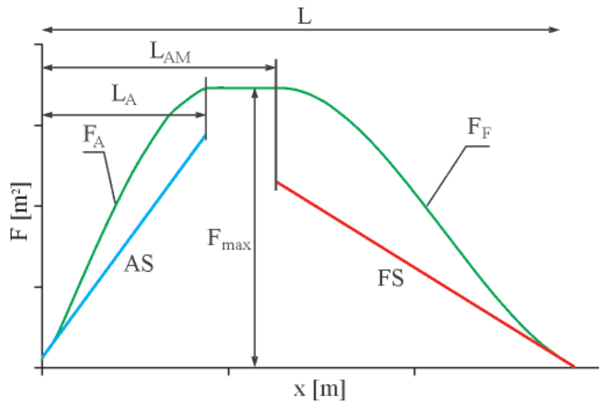

Fig. 5. The curve of frame section areas F(x) in a parametric form

The solution of the Eqs. (3) and (4) together with the conditions: (5), (6), (7), (8), (9), (10), (11) and (12) made it possible to determine the constants as follows:

$$A = 0 \quad (13)$$

$$B = AS \quad (14)$$

$$D = (-2F_{max} + AS\, L_A)/L_A^3 \quad (15)$$

$$C = -AS/(2L_A) - 1{,}5\, D\, L_A \quad (16)$$

$$H = [2\, F_{max} - SF\, (L - L_{AM})]/(L - L_{AM})^3 \quad (17)$$

$$G = [-F_{max} - H(L^3 + 2\, L_{AM}^3 - 3L_{AM}^2 L)]/(L - L_{AM})^2 \quad (18)$$

$$F = -2\, G\, L_{AM} - 3\, H\, L_{AM}^2 \quad (19)$$

$$E = -F\, L - G\, L^2 - H\, L^3 \quad (20)$$

On the basis of the parametrized curve of frame section areas the following ship hull form parameters were formulated:

- length of stern part of hull: L_A
- length of stern part and midship body of hull: L_{AM}
- slope of the curve F(x) at aft perpendicular: AS
- slope of the curve F(x) at fore perpendicular: FS
- block coefficient of underwater stern part of hull: CBA

$$CBA = \frac{\int_0^{L_A} F(x)dx}{\nabla} \quad (21)$$

where:

L – ship length
∇ – volumetric displacement of underwater part of hull
F(x) – parametrized curve of frame section areas

❖ block coefficient of underwater bow part of hull - CBF:

$$CBF = \frac{\int_{L_{AM}}^{L} F(x)dx}{\nabla} \tag{22}$$

LIST OF MODEL VARIANTS OF SHIP'S HULL

The list of model variants of ship's hull was elaborated under the following limitations:

- ship length: L = 144 m
- frame section area in the midship body zone: F_{max} = 173 m^2
- design draught: d = 8.255 m
- length of stern part of hull: L_A = 46 ÷ 60 m
- length of stern part and midship body of hull: L_{AM} = 64 ÷ 95 m
- slope of the curve F(x) at aft perpendicular: AS = 1 ÷ 5 m
- slope of the curve F(x) at fore perpendicular: FS = 1 ÷ 5 m
- freeboard heights: FB = 0.75 ÷ 7.75 m.

Hull block coefficient values were calculated on the basis of the above given parameters (in compliance with Eqs. (21) and (22)) and amounted to:

- block coefficient of underwater stern part of hull: CBA = 0.53 ÷ 0.61
- block coefficient of underwater bow part of hull: CBF = 0.54 ÷ 0.62.

On the basis of the above given limitations and Eqs. (3) and (4) 16 model variants of underwater part of hull form were elaborated. For each of the variants, 5 variants of abovewater part of hull form were designed by applying various values of freeboard height. As a result, 80 model variants of ship's hull were obtained.

In the first phase of the research influence of initial transverse metacentric height on frequency of water ingress into the holds was analyzed.

INFLUENCE OF INITIAL TRANSVERSE METACENTRIC HEIGHT ON OCCURRENCE RATE OF WATER INGRESS INTO THE HOLDS

In order to determine influence of initial transverse metacentric height on frequency of water ingress into the holds calculations were performed by assuming ship motion parameters and wave parameters in compliance with the assumed deterministic scenario.

The calcultaions were carried out by means of SEAWAY software. This is a computer program based on the theory of two-dimensional flow around a body, by which ship motions on regular wave and irregular one can be calculated. Its validation tests, presented in [8], demonstrate a high accuracy of calculations.

The influence of the initial transverse metacentric height GM on occurrence rate of water ingress into the holds was more or less similar for all the variants of underwater part of hull form and depended first of all on the height of freeboard FB. In Fig. 6 the influence of GM on frequency of water ingress into the holds is presented for one selected variant of underwater part of hull form.

As results from Fig. 6 the metacentric height GM influences ignificantly the water ingress into the hold in the range of the freeboard (FB) value equal to or greater than 3.75 m (for smaller FB values the influence of GM is negligible). In such

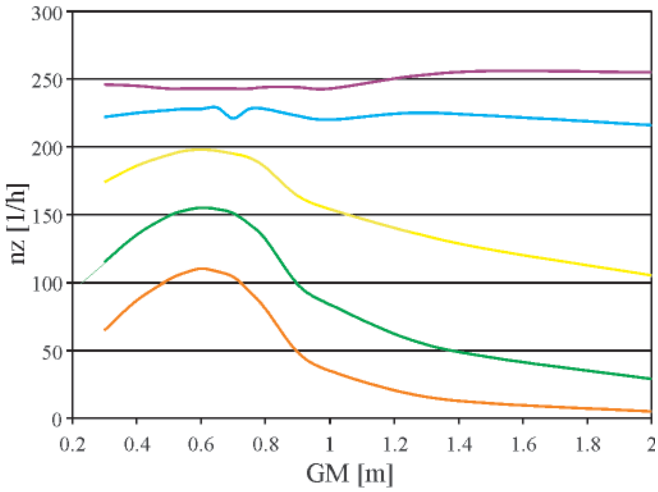

Fig. 6. *The influence of the initial transverse metacentric height GM on occurrence rate of water ingress into the hold no. 1, FB = var, the hull form parameters: L_{AM} = 95 m, L_A = 60 m, AS = 1, FS = 2.2, CBA = 0.53, CBF = 0.62, ship speed v = 10 m/s, wave encounter angle β = 60°, significant wave height H_s = 8.5 m*

cases for GM value greater than about 1 m significant drop of intensity of water ingress into the hold is observed, and the greatest intensity occurs when GM = 0.6 m.

As initial transverse metacentric height is an operational parameter dependent a.o. on ship weight and location of its centre of gravity, it is hard to consider it to be a design parameter. Hence in the further part of the research it was decided not to take the parameter into account and to conduct calculations of water ingress into the hold of model ship variants for a GM value at which the water ingress into the hold is the greatest. Such approach allows to decrease number of independent variables in regression model and leads to errors on the so called „safe side".

APPLICATION OF STATISTICAL METHODS FOR APPROXIMATION OF WATER INGRESS INTO THE HOLDS

In this part of the research calculations of water ingress into the holds were performed for all design ship variants and the assumed value of the initial transverse metacentric height GM = 0.6 m. The calculations were performed with the use of accurate methods (namely the SEAWAY software) and input data selected from operational ones resulting from the assumed deterministic scenario.

By making use of statistical methods (namely analysis of variance) and those based on artificial neural networks (namely sensitivity analysis) it was determined which design parameters affect occurrence rate of water ingress into the holds. Next, by making use of linear regression method the following analytical relation between the crucial design parameters and the occurrence rate of water ingress into the holds, nz, was determined:

$$nz = \alpha_0 - \alpha_1 \cdot FB - \alpha_2 \cdot L_A + \\ - \alpha_3 \cdot CBF - \alpha_4 \cdot CBA \tag{23}$$

where:

- nz – statistical hourly occurrence rate of water ingress into the holds
- FB – freeboard height [m]
- L_A – length of ship hull stern part (acc. Fig. 6) [m]
- CBF – block coefficient of underwater ship hull bow part [-]
- CBA – block coefficient of underwater ship hull stern part [-]

α_0 = 1111.63
α_1 = 25.93
α_2 = 5.23
α_3 = 229.68
α_4 = 729.82.

The relation (23) is characterized of:

- high value of the determination coefficient $R^2 = 0.96$ (explained variance)
- high significance of free terms and all independent variables, being on the significance level $\alpha = 0.05$,

which proves that the proposed relations are properly adjusted to the model data.

The regression of the dependent variable *nz* indicate that all components of Eq. (23) including its free term are significant.

After transforming Eq. (23) a design guideline was achieved for determining the minimum freeboard height, FB, in assumed operational conditions and for an arbitrary value of the hourly occurrence rate of water ingress into the holds, nz:

$$FB = \frac{\alpha_0 - \alpha_2 \cdot L_A - \alpha_3 \cdot CBF - \alpha_4 \cdot CBA - nz}{\alpha_1} \tag{24}$$

SUMMARY

In this paper the influence was presented of ship hull form parameters on water ingress into the holds, that made it possible the formula for elaborating the minimum value of freeboard height for open-top containership. The presented method may be used in the preliminary designing of ships of this type. The investigations were performed by applying a method complying with the concept of „goal-oriented" approach to formulation of design criteria, proposed by IMO. Such approach made it possible to elaborate relatively accurate approximations and practical guidelines for designing the open-top containerships and provides comprehensive information on merits of a considered ship already in the preliminary designing phase.

The discussed investigations consitute only a part of research on influence of ship design parameters on the phenomenon of water ingress into the holds. Such investigations should be extended to research on influence of ship dimensions on water ingress into the holds. It may be expected that after determination of crucial ship dimension parameters affecting the water ingress into the holds it would be possible to make the coefficients in Eqs. (23) and (24) dependent on the parameters. Results of such research may be very useful in solving the design problems of open-top containerships.

As results from [1, 2, 3, 4] the linear relation between the occurrence rate of water ingress into the holds, nz, and the volumetric rate of water ingress into the holds, V_{gw}, may be applicable:

$$nz = \alpha \cdot V_{gw} \tag{25}$$

where:
nz – hourly occurrence rate of water ingress into the holds
α – a constant
V_{gw} – hourly volumetric rate of water ingress into the holds.

For determination of α − value to carry out additional investigations is necessary. Knowing the α − value, one is able, on the basis of Eqs. (23) and (24), to elaborate a design criterion for determining the minimum freeboard height, which takes into account the phenomenon of water ingress into the holds. It is possible that such research may be based on determination of influence of exceedance of the freeboard height H0 [acc. Eq. (1)] on the volumetric rate of water ingress into the holds, V_{gw}.

As resulted from the performed investigations, the phenomenon of green water ingress into the holds is affected by the initial transverse metacentric height. And, the parameter, being operational one, depends on ship load conditions and hence it can be hardly considered a design parameter. Fig. 7 presents the relations which take into account influence of the metacentric height and freeboard height on water ingress into the holds for a ship of constant dimensions. Such relations may be used to plan, in the ship operation phase, a ship loading state in advance of ship departure.

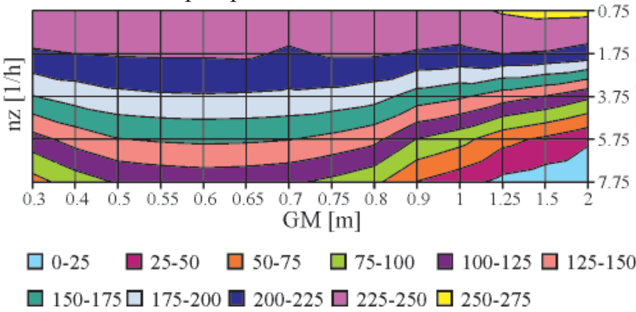

Fig. 7. *Statistical hourly occurrence rate of water ingress into the holds, nz, in function of the initial transverse metacentric height GM and the freeboard height FB; for open-top containership of the length L = 144 m, at speed v = 10 m/s, wave encounter angle β = 60°, and significant wave height* H_s *= 8.5 m*

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