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S. Grochowalski

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Schriftenreihe Schiffbau
Schwarzenbergstraße 95c
D-21073 Hamburg

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The Prediction of Deck Wetting in Beam Seas in the Light of Results of Model Tests

by

S. Grochowalski

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ABSTRACT

The theoretical model of shipping water on deck in beam seas based on the linear theory and the main statistical parameters which may describe the intensity of this phenomenon have been presented.

The influence of wind and drift on the characteristics of water level motions at the ship's side and on the statistical parameters of exceeding freeboard have been taken into account.

The comprehensive model tests carried out both in a model tank and on natural wind waves on a lake have been described. A method of analysis of the experimental results and the main effects of this analysis have been presented. They have been compared with results of numerical calculations based on the presented theoretical model.

The statistical parameters for **exceeding** bulwark edge obtained both experimentally and theoretically are in sufficient agreement.

NOMENCLATURE

- A_w - waterplane area
- $\bar{A}_i$ - relative amplitude of reflected wave
- D_u - variance of random process "u"
- $D_{\dot{u}}$ - variance of rate of change of process "u"
- F - height of ship's side measured from still waterline to upper bulwark edge
- F_o - freeboard height
- F_N - bulwark height
- F_w - change in draught of side due to heel θ_s
- g - acceleration due to gravity
- $\overline{GM}_o$ - initial metacentric height
- $\bar{h}$ - mean value of water oscillations on ship's side
- $h(t)$ - instantaneous position of the water level on the ship's side, resulting from ship motions on the wave
- $h_w(t)$ - relative motions on ship's side caused by the action of the varying wind moment
- $h_T(t)$ - resultant instantaneous water level height on ship's side
- δh_i - deformation of wave profile caused by the component of orbital motion in "i" direction
- J_{xx} - mass moment of inertia of ship about G-X axis
- $K_u(\tau)$ - auto-correlation function of process "u"
- k - wave number
- L - ship length
- $M_F(t)$ - hydrodynamic wave heeling moment
- $M_w(t)$ - variable wind heeling moment
- $\bar{M}_w$ - steady wind heeling moment
- m_{ij} - added mass in the direction "i" caused by motion in direction "j"
- m^D_{ij} - diffractive added mass - " -
- N_{ij} - damping coefficient - " -
- N^D_{ij} - diffractive damping coefficient - " -
- "N" - index for weather side
- $\bar{N}_F$ - mean number of exceedances in time T*
- $\bar{n}_F$ - mean number of exceedances in 1 second
- $\overline{OM}$ - distance of the metacentre from the origin of the moving axes
- $\overline{OG}$ - distance of the c.g. from the origin of the moving axes
- P - probability
- $\bar{p}$ - mean wind pressure
- p_o - wind pressure fluctuation amplitude
- $\delta p(t)$ - pressure fluctuations about the mean value
- r_o - wave amplitude
- S - area presented to wind
- $S_u(\omega)$ - spectral density function of process "u"
- $S_{\zeta w}(\omega)$ - wave spectrum
- T - ship's draught
- $\bar{T}_h$ - mean period of ship's side relative motions
- t - time
- V_{dr} - drift velocity of ship
- $\bar{V}_w$ - mean wind velocity
- $\delta V_w(t)$ - wind velocity oscillations about the mean value
- "Z" - index for lee side

$Z_F(t)$ - vertical component of the hydrodynamic wave excitation force
z_o - centre of drift resistance
z_s - centre of area presented to wind
$Y_F(t)$ - horizontal component of the hydrodynamic wave excitation force
$Y_w(t)$ - variable horizontal wind-exciting force
$\bar{Y}_w$ - steady horizontal wind force
Y_{dr} - side resistance of drift
y - half-width of transverse hull section under consideration
α - wave slope
β_i - phase shift due to "i" motion relative to wave
γ - specific grávity of water
Δ - ship displacement
$\delta_i(\omega)$ - response amplitude operator of motion "i" (R.A.O.)
$\delta_h(\omega)$ - R.A.O. of relative motions of water surface at ship's side caused by waves
$\delta_{hw}(\omega)$ - R.A.O. of relative water surface motions caused by wind rolling
$\delta_{\varphi w}(\omega)$ - R.A.O. for wind rolling
Φ^* - undisturbed wave potential
$\Phi_h(i\omega)$ - transfer function for relative motions on ship's side caused by wave induced hull motions
$\Phi_w(i\omega)$ - transfer function for relative motions on ship's side caused by wind
η_G, ζ_G - co-ordinates of the ship's centre of gravity in the stationary co-ordinate system
$\eta_o, \zeta_o, \varphi_o$ - hull motions amplitudes: sway, heave, roll
η_w, ζ_w - co-ordinates of a wave particle undergoing orbital motions, relative to the stationary co-ordinate system
φ - variable heel angle of ship
θ_s - static ship heel
κ_i - wave exciting force or moment coefficient taking into account the effect of the ratios of ship hull dimensions to the wave length
ω - angular frequency
ω_φ - natural frequency of rolling
ω_ζ - " " of heaving
$\bar{\omega}_h$ - mean angular frequency of ship's side relative motions
ρ - specific density of water
ρ_p - " " of air
$\bar{\tau}$ - mean period of duration of single exceedance
$\overline{\Delta h}$ - mean height of single exceedance
$\zeta_w(t)$ - undisturbed wave profile

1. INTRODUCTION

Opinions on the effect of the shipping of green water on ship safety are divided. However the opinion predominates that deck wetting presents a real danger to small, low freeboard ships, especially fishing vessels. Deck wetting endangers the crew working on the deck and hinders ship operations such as fishing. Moreover intensive deck wetting may lead to the accumulation of water on the deck, the weight of which may be significant relative to the ship's displacement. In such a case there may occur a significant reduction in stability followed by a capsize in waves.

These problems have been reflected in some of the paragraphs in the "Torremolinos '77" Convention on Fishing Vessel Safety.

As far as large vessels are concerned, opinions on the effect of deck wetting are various. The mass of water on deck is insignificant in relation to the displacement and loss of stability is minimal. In fact water on deck may even act as a roll stabilizer (e.g. [1]). So, although deck wetting may constitute a danger as far as structural safety is concerned (e.g. in large tankers [3]), it may be concluded that stability safety is unaffected.

However, capsize experiments recently carried out at the Hamburg Ship Model Basin indicate the necessity of verifying these conclusions. A detailed analysis of films taken during the experiments shows the significance of the submergence of the bulwark.

Bulwark and deck edge submergence may radically alter the rolling characteristic by preventing the ship from rolling back to the vertical position. This results in a phase shift between the roll and wave motions and hence alters the initial conditions prior to the arrival of the next wave group. As a result of a small restoring moment the ship may take such a long time to return to its upright position that the next large wave may capsize it.

For large ships, this effect is probably attributed to due to the hydrodynamic resistance presented by the bulwark motion rather than to the load of the water on deck.

The phenomenon is characterised by the longitudinal axis of roll shifting from the c.g. to the vicinity of deck edge about which the ship pivots. The heeling moment due to the wave is further enhanced by a moment resulting from the hydrodynamic force causing heaving (fig.1a).

A particularly dangerous condition arises when the bulwark submerges in quartering seas. The impact of a steep quartering wave on the stern causes a lateral hull movement combined with a rotation about a vertical axis (sway and yaw) coinciding with a leeward heel. If as a result of this movement the bulwark submerges further lateral motion causes the deck to "plough under" the water (fig.1b). These results an increase in the hydrodynamic resistance to the lateral motion which causes an increase in the heeling moment. If at the same time a large, steep wave moving along the hull from the stern towards midships, causes a large heaving force directed upwards, then there arises an additional heeling moment, as described above. Since the lateral stability one the wave crest is considerably reduced, the described event usually results in a capsize. Therefore, for very dynamic motions in quartering seas the submerged bulwark and deck edge can act as a pivot and severely increase the probability of capsize. Analogous events in which the vessel heeled to large angles passed safely if the bulwark and deck edge did not become submerged.

It may be seen then that in distinction from deck wetting of small ships, where loss of safety may arise from the accumulation of water on deck, large ships may encounter dangerous situations resulting from a radical change in the motion caused by deck edge immersion. In this case it would be more correct to talk of deck-edge submergence rather than deck wetting. In both cases however, the occurrence of the phenomenon is dependent on the relative motion between bulwark edge and wave.

In the light of the observations made previously, it may be stated that the safety of every vessel may be endangered by the bulwark becoming submerged.

The submergence of the upper edge of the bulwark could then be accepted as one of the ship safety criteria*. In order to do this it would be necessary to theoretically predict the occurrence of the phenomenon for given weather conditions, and to estimate its intensity.

A theoretical model for deck wetting in beam seas based on relative motion between wave and deck edge has in the past been prepared by the author ([4], [5]). This theoretical model was verified by correlation with model tests in regular tank waves as well as in natural waves in a lake.

This paper compares the model test results with theoretical predictions.

2. A MATHEMATICAL MODEL OF RELATIVE MOTIONS OF WATER SURFACE AT THE SHIP'S SIDE

The derivation of the expressions describing relative motions on the ship's side and the analysis of the problem are to be found in [5]. Here only the main steps leading to the final expressions are given.

The following assumptions were made initially:

- Wind and waves act upon the vessel simultaneously. The vessel lies beam on to the incoming waves and drifts freely. The forward velocity of the vessel is zero;
- the two-dimensional wave motion is a stochastic, stationary and ergodic process having a normal probability density distribution;
- for the considered interval of time, the mean wind velocity is constant and the wind velocity oscillations about this value are a stochastic process which is uncorrelated with the wave motions;
- the flow around the hull is potential and two-dimensional. Viscous damping forces are only significant for roll damping;
- the hull executes motions which may be described by a set of linear differential equations. Non-linear damping and restoring moments should be accounted for by a linearization technique;
- the amount of water on deck does not basically influence the motions in waves.

The axes fixed in space on the water surface $O\xi\eta\zeta$ and ship's body axes $OXYZ$ were chosen as shown in fig.2 .

The following ship's motions equations were formulated in accordance with the assumptions given above:

sway:

$$\left(\frac{\Delta}{g}+m_{yy}\right)\ddot{\eta}_G+N_{yy}\dot{\eta}_G+m_{y\varphi}\ddot{\varphi}+N_{y\varphi}\dot{\varphi}=Y_F(t)+Y_W(t)$$

roll:

$$\left(J_{xx}+m_{\varphi\varphi}\right)\ddot{\varphi}+N_{\varphi\varphi}\dot{\varphi}+m_{\varphi y}\ddot{\eta}_G+N_{\varphi y}\dot{\eta}_G+\Delta\overline{GM}_o\varphi=M_F(t)+M_W(t) \qquad (1)$$

heave:

$$\left(\frac{\Delta}{g}+m_{zz}\right)\ddot{\zeta}_G+N_{zz}\dot{\zeta}_G+\gamma A_W\zeta_G=Z_F(t)$$

The assumed linearity of the dynamics and the assumed independence of waves on the instantaneous wind speed make possible the application of superposition and the separation of motions and deck wetting caused by wave and by wind.

2.1 The Oscillations of the Water Level on Ship's Side, Caused by Regular Beam Waves

The hydrodynamic exciting forces and moments in equation (1) are given as follows:

$$Y_F(t)=\varkappa_\eta\frac{\Delta}{g}\ddot{\eta}_w+m^D_{yy}\ddot{\eta}_w+N^D_{yy}\dot{\eta}_w+m^D_{y\varphi}\ddot{\alpha}+N^D_{y\varphi}\dot{\alpha}$$

$$M_F(t)=\varkappa_\varphi\Delta OM\alpha+m^D_{\varphi\varphi}\ddot{\alpha}+N^D_{\varphi\varphi}\dot{\alpha}+m^D_{\varphi y}\ddot{\eta}_w+N^D_{\varphi y}\dot{\eta}_w+\overline{OG}\,Y_F(t) \qquad (2)$$

$$Z_F(t)=\varkappa_\zeta\gamma A_W\zeta_w+m^D_{zz}\ddot{\zeta}_w+N^D_{zz}\dot{\zeta}_w$$

The wave velocity and acceleration components appearing in the above equation were derived from the well known relations:

$$\zeta_w=\frac{1}{g}\frac{\partial\Phi^*}{\partial t}\bigg|_{\zeta=0}\ ;\quad \dot{\eta}_w=\frac{\partial\Phi^*}{\partial\eta}\bigg|_{\zeta=0}\ ;\quad \alpha=\frac{\partial\zeta_w}{\partial\eta} \qquad (3)$$

where the velocity potential Φ^* of the undisturbed flow is geven by the following form:

$$\Phi^*=\frac{i r_o g}{\omega}\exp\left[-k\zeta+i(k\eta-\omega t)\right] \qquad (4)$$

Assuming that the added mass and damping coefficients appearing in equations (1) and the corresponding diffractive added mass and damping coefficients in (2) are known, it is possible to solve (1).

Since the steady-state motions are of interest, particular integrals of the following form are sought:

$$\varphi=\varphi_o\cos(\omega t+\beta_\varphi)$$

$$\eta_G=\eta_o\cos(\omega t+\beta_\eta) \qquad \zeta_G=\zeta_o\cos(\omega t+\beta_\zeta) \qquad (5)$$

The solution of (1) gives the amplitudes φ_o, η_o, ζ_o, and the phases β_φ, β_η, β_ζ.

The instantaneous water level h(t) on the ship's side is the result of the hull motions, the wave motion and the distortion of the wave on the ship's side. The method for determining the water level on the ship's side is shown on fig.2 . Let us consider for example, the lee side.

The water level height $h_z = \overline{ZZ'}$ relative to the calm water waterline (point Z) in the position "1" is given by

$$h_z(t)=\frac{h^*_z(t)}{\cos\varphi} \quad \text{where} \quad h^*_z(t)=\zeta_w(t)\Big|_{\eta_{z'}}-\zeta_z(t) \qquad (6)$$

The vertical ordinate for Z is :

$$\zeta_z=\zeta_{G'}+y\sin\varphi-\overline{OG}\cos\varphi=\overline{OG}+\zeta_G+y\sin\varphi-\overline{OG}\cos\varphi$$

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* It should be noted that the bulwark-edge immersion as discussed here should not be confused with deck-edge or bulwark-edge immersion determined for static calm water conditions, hitherto in use.

and the abscissa of Z' is :

$$\eta_{z'} = \eta_z - \overline{Z'Z}\sin\varphi = \eta_G + y\cos\varphi + \overline{OG}\sin\varphi - \overline{Z'Z}\sin\varphi$$

Simplifying in accordance with the linear theory gives:

$$\eta_{z'} \cong \eta_G + y \qquad \zeta_z \cong \zeta_G + y\varphi \qquad h_z(t) \cong h_z^*(t) \tag{7}$$

By taking into account the distortion of the wave profile $\delta\zeta_w$ at the position having absciss $\eta_{z'}$, the water level on the lee side may be expressed by :

$$h_z(t) = \zeta_w(t, \eta_{z'}) + \delta\zeta_w(t, \eta_{z'}) - \zeta_G(t) - y\varphi(t) \tag{8}$$

where the functions $\zeta_G(t)$ and $\varphi(t)$ are given by (5).

The time dependent co-ordinate $\eta_{z'}$ shows the direct influence of sway on the ship's side water level height, resulting from the hull's change of position relative to the wave profile.

The resulting wave profile may be expressed in terms of the body axes by:

$$\zeta_w(t) = r_0 \cos[k\eta_0 \cos(\omega t + \beta_\eta) + ky - \omega t] \tag{9}$$

As can be seen the regular wave ceases to be harmonic in the moving co-ordinate system, since the argument of the cosine function is another time dependent harmonic function.

Further analysis showed however that the difference between the wave profile in the stationary co-ordinate system and the apparently distorted profile relative to body axes, is very small for waves having a high wave length to wave height ratio and may therefore be ignored in computations. Therefore, the direct effect of sway may be ignored and it may be assumed that $\eta_{z'} \cong y$.

The determination of wave profile distortion in a form which may be applied analytically is difficult. In order to determine the resulting deformed wave profile on the ship's side it is necessary to determine the resultant velocity potential Φ_v which is the sum of the radiation potential Φ_R, the undisturbed wave potential Φ^* and the diffraction potential Φ_D. It is then possible to find the amplitude and phase of the deformed wave profile from the free surface boundary condition :

$$(\zeta_w + \delta\zeta_w) = \frac{1}{g} \left. \frac{\partial \Phi_v(\pm y)}{\partial t} \right|_{\zeta=0} \tag{10}$$

Hitherto the resultant potential Φ_v for a hull rolling in waves could only be determined numerically. (Computations of wave profile distortion based on (10) using the multipole potential method has later carried out Dudziak [2]). However, it seems that if the calm water added mass and damping coefficients and diffraction coefficients are known, then it would be possible to formulate an analytical expression for the wave profile deformation, based on existing theoretical papers.

A hull oscillating on the calm water surface generates a system of progressive waves travelling to infinity (damping), and local disturbances taking the form of standing waves (added mass) [8] .

The well-known relationship between the amplitude of the generated progressive wave and the motion damping (per unit length) is following :

$$N'_{ii} = \frac{\rho g^2}{\omega^3} \bar{A}_{ii}^2 \tag{11}$$

If the reverse situation is now considered in which the progressive wave meets a stationary hull then as a result of the impact and deformation of the wave, a similar phenomenon to that described previously, occurs i.e. local disturbance and a reflected progressive wave. The quantitative relations between the parameters of these systems of waves and the respective diffractive elements of the wave exciting force must be the same as before, since the physical nature of the phenomenon is the same ([7],[9]).

This paper has described that part of the deformation which is considered to dominate i.e. the deflection and reflection of the incoming exciting wave. The diffractive damping of the wave exciting force is related to this phenomenon.

Resolving the orbital motion of the particles of the exciting waves into two components in the directions of the axis $0\text{-}\eta$ and $0\text{-}\zeta$, and making use of the dependence (11), the relative amplitudes of the reflective waves may be defined as :

$$\bar{A}_\zeta = \frac{\delta h_{\zeta 0}}{r_0} = \sqrt{\varkappa \frac{N'_{zz}\omega^3}{g^2\rho}} \quad ; \quad \bar{A}_\eta = \frac{\delta h_{\eta 0}}{r_0} = \sqrt{\varkappa \frac{N'_{yy}\omega^3}{g^2\rho}} \tag{12}$$

where according to [10] is taken :

$$N_{ii}^D = \varkappa N_{ii} \quad ; \quad \varkappa = e^{-kT} \frac{\sin\frac{2\pi y}{\lambda}}{\frac{2\pi y}{\lambda}} \tag{13}$$

The generation of reflected waves is directly related to the wave particle velocity. It has been therefore assumed that the maximum values δh_ζ and δh_η occur at the moment when they attain the maxima of ζ_w and $\dot{\eta}_w$. Taking into account in addition, that in view of the reflection phenomenon, the sign of the deformation should be opposite to that of the component velocities in the undisturbed wave, the phase and general form of the reflected wave is taken to be as follows :

$$\delta h_\zeta = r_0 \bar{A}_\zeta \cos\left[(k\eta - \omega t) + \frac{\pi}{2}\right]$$

$$\delta h_\eta = \begin{cases} r_0 \bar{A}_\eta \cos(k\eta - \omega t) & \text{for the weather side} \\ -r_0 \bar{A}_\eta \cos(k\eta - \omega t) & \text{for the lee side} \end{cases} \tag{14}$$

The height of water level on the lee side may now be written as follows :

$$h_z(t) = r_0\cos(ky - \omega t) + r_0 \bar{A}_\zeta \cos\left(ky - \omega t + \frac{\pi}{2}\right) + \tag{15}$$
$$- r_0 \bar{A}_\eta \cos(ky - \omega t) - \zeta_0 \cos(\omega t + \beta_\zeta) - y\varphi_0 \cos(\omega t + \beta_\varphi)$$

The above function called next as "the function of water oscillations on the lee side" is the sum of harmonic functions having the same frequency ω and may therefore be written as

$$h_z(t) = r_0 \delta_{hz} \cos(\omega t + \beta_z) \tag{16}$$

where the amplification factor δh_z and phase β_z are determined from :

$$\delta_{hz}(\omega)=[y^2\delta_\varphi^2+\delta_\zeta^2+\bar{A}_\zeta^2+(1-\bar{A}_\eta)^2+2y\delta_\varphi\delta_\zeta\cos(\beta_\varphi-\beta_\zeta)+$$
$$+2y\delta_\varphi\bar{A}_\zeta\sin(\beta_\varphi+ky)-2y\delta_\varphi(1-\bar{A}_\eta)\cos(\beta_\varphi+ky)+ \quad (17)$$
$$+2\delta_\zeta\bar{A}_\zeta\sin(\beta_\zeta+ky)-2\delta_\zeta(1-\bar{A}_\eta)\cos(\beta_\zeta+ky)]^{\frac{1}{2}}$$

$$tg\beta_z=\frac{-y\delta_\varphi\sin\beta_\varphi-\delta_\zeta\sin\beta_\zeta-\bar{A}_\zeta\cos ky-(1-\bar{A}_\eta)\sin ky}{-y\delta_\varphi\cos\beta_\varphi-\delta_\zeta\cos\beta_\zeta-\bar{A}_\zeta\sin ky+(1-\bar{A}_\eta)\cos ky} \quad (18)$$

Similarly, the function describing water oscillations on the weather side has been derived :

$$h_N(t)=r_0\delta_{hN}\cos(\omega t+\beta_N) \quad (19)$$

$$\delta_{hN}(\omega)=[y^2\delta_\varphi^2+\delta_\zeta^2+\bar{A}_\zeta^2+(1+\bar{A}_\eta^2)-2y\delta_\varphi\delta_\zeta\cos(\beta_\varphi-\beta_\zeta)+$$
$$-2y\delta_\varphi\bar{A}_\zeta\sin(\beta_\varphi-ky)+2y\delta_\varphi(1+\bar{A}_\eta)\cos(\beta_\varphi-ky)+ \quad (20)$$
$$+2\delta_\zeta\bar{A}_\zeta\sin(\beta_\zeta-ky)-2\delta_\zeta(1+\bar{A}_\eta)\cos(\beta_\zeta-ky)]^{\frac{1}{2}}$$

$$tg\beta_N(\omega)=\frac{y\delta_\varphi\sin\beta_\varphi-\delta_\zeta\sin\beta_\zeta-\bar{A}_\zeta\cos ky+(1+\bar{A}_\eta)\sin ky}{y\delta_\varphi\cos\beta_\varphi-\delta_\zeta\cos\beta_\zeta-\bar{A}_\zeta\sin ky+(1+\bar{A}_\eta)\cos ky} \quad (21)$$

2.2 The Influence of Wind on the Oscillations of Water Level on the Ship's Side

The influence of the wind is characterized by changes in the ship's response.

In accordance with the assumptions, the instantaneous wind velocity may be considered to be the sum of a constant mean velocity $\bar{V}_w$ and the velocity pulsations $\delta V_w(t)$ about the mean.

The mean pressure $\bar{p}$ (corresponding to $\bar{V}_w$) results in a constant horizontal force $\bar{Y}_w$ causing drift and a constant heeling moment $\bar{M}_w$.

$$\bar{Y}_w=k_w\bar{p}S=k_wS\frac{\varrho_p\bar{V}_w^2}{2} \quad (22)$$

$$\bar{M}_w=k_w\bar{p}S(z_s-z_0) \quad (23)$$

The drift is resisted by a side force Y_{dr} :

$$Y_{dr}=k_sLT\frac{\varrho V_{dr}^2}{2} \quad (24)$$

The drift velocity may be determined by equating (22) and (24):

$$V_{dr}=\bar{V}_w\sqrt{\frac{\varrho_p k_w S}{\varrho k_s LT}} \quad (25)$$

The non-dimensional coefficients k_w and k_s are usually determined experimentally.

The influence of drift on rolling and consequently on the characteristics of water oscillations on the ship's side, appears as a change in the excitation frequency :

$$\omega_e=\omega-kV_{dr}$$

The moment $\bar{M}_w$ causes a static heel Θ_s towards the leeward side,

$$\Theta_s=\frac{\bar{M}_w}{\Delta\,\overline{GM}_0} \quad (26)$$

about which the ship rolls.

Consequently the mean draught on each side changes by :

$$F_w=y\Theta_s \quad (27)$$

i.e. decreases on the weather side and increases on the lee side.

The pressure pulsations $\delta p(t)$ (corresponding to $\delta V_w(t)$) causes a time varying aerodynamic horizontal force :

$$\delta Y_w(t)=k_wS\,\delta p(t) \quad (28)$$

and moment :

$$\delta M_w(t)=k_wS(Z_s-\overline{KG})\delta p(t) \quad (29)$$

The varying moment $\delta M_w(t)$ causes rolling which is similar in theory to that caused by waves. Assuming that the pressure pulsations about the mean value are a random continuous stationary process, it is possible to express them as a harmonic series. The rolling characteristic may then be determined by solving the equations of motion (1) and expressing the exciting forces and moments by (28) and (29) while assuming the wave excitation to be zero.

As a result, the amplification factor for wind excited rolling $\delta_{\varphi w}$ and the amplification factor $\delta_{\xi w}$ for horizontal oscillations are obtained.

In view of the great inertia of the vessel as well as the large side force Y_{dr} relative to the small values and short duration of the force $\delta Y_w(t)$, the sway caused by wind fluctuations is negligible.

The wind rolling will cause symmetric water level oscillations on the ship's side, given by :

$$h_w(t)=y\,p_0\,\delta_{\varphi w}(\omega)\sin(\omega t+\varepsilon_\varphi) \quad (30)$$

where the R.A.O. for these oscillations per amplitude of exciting wind pressure, is given by:

$$\delta_{hw}(\omega)=y\,\delta_{\varphi w}(\omega) \quad (31)$$

2.3 Water Oscillations on the Ship's Side in Natural Conditions

In natural conditions, the wind and waves act on the ship simultaneously. The resultant water level on the ship's side $h_T(t)$ is the sum of wind oscillations and wave oscillations:

$$h_{T_{\frac{N}{Z}}}(t)=h_{\frac{N}{Z}}(t)+h_w(t)\pm y\Theta_s \quad (32)$$

where the index "N" - indicates the weather side and "Z" - the lee side.

Since the waves and wind are continuous random stationary processes and the ship motions are described by a set of linear differential equations, then the function describing water level oscillation on the ship's side, is also a continuous random, stationary function.

For known statistical characteristics for waves $\zeta_w(t)$ and wind $\delta p(t)$ it is possible to determine the statistical characteristics of the ship's side water oscillations on condition that their transfer function is known.

The water level oscillation can be described in the following complex form :

$$H_{T_{\frac{N}{Z}}}(t)=\Phi_{h_{\frac{N}{Z}}}(i\omega)\zeta_w(t)+\Phi_w(i\omega)\delta p(t)\pm y\Theta_s \quad (33)$$

where the wave induced water level oscillation transfer function has the form :

$$\Phi_h(i\omega)=\delta_h(\omega)e^{-i\beta} \quad (34)$$

and the wind induced transfer function is given by :

$$\Phi_w(i\omega) = \delta_{hw}(\omega) e^{-i\varepsilon_\varphi} \qquad (35)$$

The response amplitude operator (R.A.O.) for wave-induced oscillation $\delta_h(\omega)$ is determined from (17) for the lee side and from (20) for the weather side. The respective phase characteristics are given by (18) and (21). The R.A.O. for wind induced oscillations is given by (31).

The variances of the water level oscillations (D_T) and of the velocity of oscillations ($D_{\dot{T}}$) are given by :

$$D_{T_z^N} = \int_0^\infty S_{h_z^N}(\omega)d\omega + \int_0^\infty S_{hw}(\omega)d\omega = D_{h_z^N} + D_{hw} \qquad (36)$$

$$D_{\dot{T}_z^N} = \int_0^\infty \omega^2 S_{h_z^N}(\omega)d\omega + \int_0^\infty \omega^2 S_{hw}(\omega)d\omega = D_{\dot{h}_z^N} + D_{\dot{h}w} \qquad (37)$$

where the wave induced oscillation spectrum is given by :

$$S_{h_z^N}(\omega) = \left[\delta_{h_z^N}(\omega)\right]^2 S_{\zeta w}(\omega) \qquad (38)$$

and the wind induced spectrum :

$$S_{hw}(\omega) = \left[\delta_{hw}(\omega)\right]^2 S_p(\omega) \qquad (39)$$

In reality, the varying wind induced heeling moment is very small compared to the moment of inertia of the ship and wave excitation moment. Consequently, the amplitudes of wind rolling are very small and their effect on the ship's side water oscillations and their variance are negligible. It can therefore be neglected in practical calculations and only wave induced oscillation variance be considered :

$$D_T \cong D_h = \int_0^\infty S_h(\omega)d\omega \quad ; \quad D_{\dot{T}} \cong D_{\dot{h}} = \int_0^\infty \omega^2 S_h(\omega)d\omega \qquad (40)$$

As in the case of waves, the probability density of instantaneous values of the oscillation function h(t) is normally distributed whereas the amplitudes of the oscillations are a Rayleigh distribution. The probabilistic properties of the function h(t) are shown on fig.3 .

By determining the variances D_h and $D_{\dot{h}}$ for each side it is possible to obtain all the statistical characteristics of the relative motions on ship's sides.

3. STATISTICAL CHARACTERISTICS OF DECK WETTING

It has been assumed that deck wetting occurs when the water level rises above the upper edge of the bulwark. On the basis of this definition the evaluating of shipping water on deck resolves itself to the determination of the statistical characteristics of the exceedances of a level F by a random function h(t) (see fig.4) :

$$h(t) > F$$

The derivation of the parameters characterizing the intensity of wetting and a discussion of them may be found in [6]. The basic characteristics are following :

The probability of deck wetting

a) assuming that deck wetting occurs when the value of function h(t) exceeds the height of the freeboard (from normal distribution):

$$P_\tau = P(h > F_0 \pm F_w) = \frac{1}{2} - \Phi\left(\frac{F_0 \pm F_w}{\sqrt{D_T}}\right) \qquad (41)$$

where: $\Phi(x) = \frac{1}{2\pi}\int_0^x e^{-\frac{t^2}{2}}dt$ - Laplace integral function,

variance D_T - calculated by (36) or (40) respectively for the weather or lee side,

F_w - is taken with "+" for the weather side and "-" for the lee side.

The quantity P_τ can be interpreted as the ratio of the total duration of the exceedances to the total duration of the process (fig.4) :

$$P_\tau = \frac{\sum_{i=1}^N \tau_i}{T^*} \qquad (42)$$

b) assuming that the deck wetting takes place when the amplitude h_0 of the water level oscillations exceeds the height of the freeboard (from Rayleigh's distribution):

$$P_F = P(h_0 > F_0 \pm F_w) = \exp\left[-\frac{(F_0 \pm F_w)^2}{2D_T}\right] \qquad (43)$$

The probability may be interpreted as the ratio of the number of exceedances to the total number of amplitudes h_0 , during the time interval T^* :

$$P_F = \frac{n}{N} \qquad (44)$$

Mean exceedance height

$$\overline{\Delta h} = \sqrt{\frac{\pi}{2} D_T}\left[1 - 2\Phi\left(\frac{F_0 \pm F_w}{\sqrt{D_T}}\right)\right] \exp\frac{(F_0 \pm F_w)^2}{2D_T} \qquad (45)$$

Mean number of exceedances in time T^*

$$\bar{N}_F = \frac{\bar{\omega}_h T^*}{2\pi} \exp\left[-\frac{(F_0 \pm F_w)^2}{2D_T}\right] \qquad (46)$$

where $\bar{\omega}_h = \sqrt{\frac{D_{\dot{T}}}{D_T}}$ - mean frequency of water oscillations on the ship's side

The probability, that n exceedances occur in time T^* :

$$P_n = P(n|T^*) = \frac{\bar{N}_F^n}{n!} e^{-\bar{N}_F} \qquad (47)$$

where $\bar{N}_F$ is determined from (46).

Mean duration of a single deck wetting event :

$$\bar{\tau} = \frac{\pi}{\bar{\omega}_h}\left[1 - 2\Phi\left(\frac{F_0 \pm F_w}{\sqrt{D_T}}\right)\right] \exp\frac{(F_0 \pm F_w)^2}{2D_T} \qquad (48)$$

The probability that the deck wetting period is greater than t^* :

$$P_t = P(\tau > t^*) = \exp\left(-\frac{t^*}{\bar{\tau}}\right) \qquad (49)$$

where the mean duration of deck wetting $\bar{\tau}$ is given by (48).

All the discussed statistical exceedance parameters are functions of the freeboard height F, as well as being dependent on the dynamic characteristics of the ship ($\delta_h(\omega)$) and on the wave and wind spectra $S_{\zeta w}(\omega)$, $S_p(\omega)$ (which is expressed by the variances D_τ and $D_{\dot{\tau}}$).

For a particular ship and for a particular sea state the exceedance parameters are directly related to each other.

The relations between three main ones ($\overline{\Delta h}$, $\bar{\tau}$, $\bar{N}_F$) are as follows :

$$\overline{\Delta h} = \frac{P_\tau}{P_F}\sqrt{2\pi D_\tau} \quad (50) \qquad \bar{N}_F = \frac{T^*}{\bar{T}_h} P_F \quad (51)$$

$$\bar{\tau} = \frac{P_\tau}{P_F}\bar{T}_h \quad (52) \qquad \overline{\Delta h} = \sqrt{\frac{D_{\dot{\tau}}}{2\pi}}\,\bar{\tau} \quad (53)$$

where $\bar{T}_h = \frac{2\pi}{\bar{\omega}_h}$

These relations confirm the intuitive understanding of this phenomenon.

The most interesting relation is the common dependency of the mean duration $\bar{\tau}$ of a single exceedance and the mean exceedance height $\overline{\Delta h}$, since the danger of the bulwark going under water and water on deck is governed by these two parameters.

As can be seen from (53), the mean exceedance height is directly proportional to the mean period of wetting. The magnitude of the coefficient of proportionality is governed by the variance of the velocity of water oscillations on the ship's side $D_{\dot{\tau}}$. This is affected by the character of the oscillation's transfer function $\delta_h(\omega)$ as well as by the wave spectrum $S_{\zeta w}(\omega)$ and by their relative positions.

The more the maxima of $\delta_h(\omega)$ and $S_{\zeta w}(\omega)$ are shifted to the higher frequencies, the greater $D_{\dot{\tau}}$. This means that if more energy is carried by the high frequency waves then, for a certain mean duration of a single deck wetting, the exceedance heights are greater.

For a given spectrum, the exceedances will be the higher, the greater the ship's tendency to execute high frequency motions i.e. the greater the ship's "stiffness" .

4. MODEL TESTS

Model tests on ship motions and deck wetting were carried out at the Ship Research Institute of the Technical University Gdańsk, both on regular waves in towing tank, and in natural wind-wave conditions on a lake.

A typical low-freeboard side trawler, type B-14, which is used by the polish fishing fleet, was selected. The main parameters for the 1:25 model were :

Δ = 76.0 kG	C_B = 0.56	$\overline{KG}$ =15.0 ; 15.42 cm
L_{pp}=215.4 cm	C_p = 0.63	$\overline{GM}_o$ = 2.68; 2.26 "
B = 36.0 "	C_{wp}= 0.80	J_{xx} =12.2 ; 13.5 kGcmsec^2
T = 17.3 "	C_M = 0.88	ρ_{xx}/B=0.348; 0.365
H = 19.8 "	$\overline{FM}_o$= 7.5 cm	ω_φ = 3.9 ; 3.43 sec^{-1}
F_N = 4.4 "	$\overline{KM}_o$=17.68 "	T_φ = 1.61; 1.84 sec
F_o = 2.5 "	S =3010 cm^2	
F_1 = 3.5 "	z_s=22.9 cm	
F_2 = 4.5 "	ω_ζ= 6.23sec^{-1}	

Those parts of the model above the water were made according to the full scale form of the hull with the forecastle, poop, deckhouse and the bulwarks with freeing ports (photo 1).

In order to investigate the effect of the freeboard F on the deck wetting characteristics, the freeboard could be altered by 40 % and 80 %, relative to the built height F_o, without changing the displacement, position of the centre of gravity $\overline{KG}$ or the mass moment of inertia J_{xx} .

4.1 Regular Wave Tests

The waves generated in the tank were regular, cylindrical and having a more or less sinusoidal profile. The waves travelled parallel to the towing tank's sides.

The model was positioned beam-on to the incoming waves and was free to oscillate and drift.

The following values were continuously measured and recorded :

- wave profile $\zeta_w(t)$ in fixed axes, in front of the model,
- roll $\varphi(t)$ by means of a gyroscope positioned inside the model,
- vertical $\ddot{z}(t)$ and horizontal $\ddot{y}(t)$ accelerations of the model's centre of gravity, by means of accelerometers fixed inside the hull, near to the c.g.,
- water oscillations on the sides at midships ($h_N(t)$ and $h_Z(t)$), by means of a probe mounted on each side ,
- mean drift speed.

The test program included measurements for both values of $\overline{KG}$ and for all three freeboard heights F_o, F_1 and F_2 .

The wave parameters included both the roll resonance frequency as well as the heave resonance frequency, in the range of steepnesses h/λ = 1/10 ÷ 1/60 .

The ratio of wave amplitudes to the freeboard height was from r_o/F = 0.8 ÷ 2,8 for F_o to r_o/F = 0.5 ÷ 1.5 for F_2 . With the bulwark included this was : r_o/F = 0.3 ÷ 1.1 for $(F_o + F_N)$ and r_o/F = 0.25 ÷ 0.8 for $(F_2 + F_N)$.

Therefore, the program practically included all the parameters which govern deck wetting.

The R.A.O.'s determined from these measurements for roll, heave and water oscillations on the ship's side were plotted as points on fig. 8 ÷ 13.

4.2 Model Tests in Natural Irregular Waves and Wind

The tests were carried out at the research station by the lake Jeziorak.

The same model was used with the same instrumentation as in the tank tests.

The measurements were taken from self-propelled catamaran, specially adapted for seakeeping experiments.

The electrical generators, recorders and experimenters were located on the catamaran.

The model was able to drift freely beam-on to the main direction of incoming waves, in an undisturbed region of waves. The model could move in waves in six degrees of freedom and the signals from the measuring devices were carried to the catamaran by loosely hanging cables (photo 1). The model motions and water level oscillations on its sides were measured identically as in the regular wave tests.

Moreover, the mean $\bar{V}_w$ and instantaneous $V_w(t)$ wind velocities were measured at a height ~1.2 m above the water level.

Measurements were carried out for various intensities of irregular waves motion such that the ratio of the significant wave amplitude to the freeboard height lay in the range: $h_{1/3}/2F = 1.12 \div 3.28$, or including the bulwark height: $h_{1/3}/2(F+F_N) = 0.49 \div 1.19$.

The duration of each individual measurement was long enough to be able to determine the statistical characteristics of the processes being measured (duration of measurement approx. 12 minutes, on average over 400 rolls of the model). However, the measurements were short enough for the recorded random functions to be stationary.

An example of the recorded signals is given on fig. 5.

The spectral analysis and statistical analysis of the random processes was carried out by the analogue machine ISAC-NORATOM. As a result the following characteristics were obtained for every measured process "U"

- auto-correlation function $K_u(\tau)$,
- spectral density function $S_u(n)$, where $n = \omega/2\pi$,
- distribution function of the instantaneous values F(u).

An example of the results obtained from the analog machine is shown in fig. 6.

On the basis of these results the following was obtained:

- the variance of the process, as the value of the auto-correlation function for $\tau = 0$: $D_u = K_u(0)$,
- the variance of the rate of change of the process, from the spectral density distribution: $D_{\dot{u}} = \int_0^\infty \omega^2 S_u(\omega) d\omega$,
- mean values and the probabilities of exceeding certain values of a process - directly from the distribution of instantaneous values.

On the basis of the obtained spectral densities, the R.A.O.'s was determined from the relation :

$$\delta_u(\omega) = \sqrt{\frac{S_u(\omega)}{S_{\zeta_w}(\omega)}} \qquad (54)$$

The roll and heave R.A.O.'s obtained by this method are shown as thin lines on fig. 8, 9, and the ship's side water level oscillations for both $\overline{KG}$ values - on figs. 10 ÷ 13.

Moreover fig. 7 shows the spectral densities of the measured quantities for the purpose of comparing the common relationship between them.

5. RESULTS OF COMPUTATIONS AND OF MODEL TESTS

An algorithm and program was prepared on the basis of the theoretical relations given in sections 2 and 3. This program computes the ship motions on beam seas, relative water motions on the ship's side and the variance and statistical exceedance characteristics for an input wave spectrum. The wind effect is taken into account by calculating the drift velocity V_{dr} and the static heel θ_s.

The hydrodynamic mass coefficients m_{ij} and N_{ij} were calculated by using SCORES [10]. The non-linear roll damping was taken into account by adding a viscous damping factor corresponding to the mean resonance amplitudes.

This program was used to compute transfer functions and relative motions for the model used in model tests. The computations were carried out for both positions of centre of gravity ($\overline{KG}$ = 15.0 cm and $\overline{KG}$ = 15.42 cm); with and without drift; with and without wave deformations; with all geometrical and loading parameters the same as for the model.

The computed R.A.O.'s for heave and roll for $\overline{KG}$ = 15.0 cm are shown in figs. 8, 9. Plotted over these are the R.A.O.'s obtained from both regular and irregular wave tests (for $\overline{KG}$ = 15.42 the shape of the curves and agreement of results are similar).

Generally it can be said that the formulated equations describe the hull motions in beam seas accurately. This gives a basis for checking the computations of water surface relative motions.

The relative motion R.A.O.'s for model tests and numerical computations are given on figs. 10 ÷ 13 for both $\overline{KG}$ positions.

The following may be noted :

- the comparison between results obtained from the regular wave tests and those obtained by means of spectral analysis from tests in natural irregular waves shows remarkably good agreement.
- The theoretically computed R.A.O.'s also agree with the measured results. The conformity of these results is improved, particularly for the lee side, by taking into account wave deformations.
- The R.A.O. for relative motions on the weather side has two distinct maxima : one in the roll resonance region, the other in the heave resonance region;
- for the lee side the R.A.O. has only one maximum in the roll resonance region. The magnitude of this maximum is close to that for the weather side. There is no second maximum in the short wave region. This is caused by phase shifts of particular hull motions components for the lee side and by the damping out of short waves on the leeward side.

The difference between the characteristics for the weather and lee side is distinctly shown on fig. 7, where the wind, model motion and relative water motion spectra for each side were plotted for the measurement 12. This is typical for results obtained from the tests.

As can be seen the greater deck wetting danger is decidedly on the weather side. This is also confirmed by the fact that the waves move towards the hull on the windward side, thereby favouring the conditions for wetting resulting from exceedance. This is not the case on the leeward side, on which the waves move away from the hull.

The described in section 4 program was used to compute the variance of relative motions as well as the statistical parameters of freeboard and bulwark exceedance, for all measurements taken during the wind wave tests. Each time the measured real wave spectrum and real wind speed were input to the program. The effect of wind pressure fluctuations was not taken into account because these would have been low frequency oscillating lying outside the frequencies significant for the model (see fig. 7).

The results of the computations with the wave deformation included ($A_{\eta,\zeta} \neq 0$) and without its inclusion ($A_{\eta,\zeta} = 0$), are shown with respective results obtained from measurements, on table 1.

As can be seen, the variances D_h and $D_{\bar{h}}$ are in good agreement with the real variances obtained from the measurements. Larger differences occur for some of the statistical parameters of bulwark edge exceedance. This results from the values of these parameters being small (the differences are much smaller for low values of F e.g. for a freeboard without a bulwark). In spite of this the results obtained are comparable with the results of the measurements and for all practical purposes the calculation method may be recognized as sufficiently accurate.

6. CONCLUSIONS

The theoretical considerations, numerical computations and the results of model tests carried out for medium to heavy sea states (with respect to the ship type and scale), make possible the following conclusions :

1) The relative water motions on the sides of a ship rolling in beam seas can be described sufficiently well by linear theory in cases where the deck wetting is not too intensive.
   With regard to rolling, non-linear effects can be accounted for by linearization techniques.
2) The good correlation between model test results in deterministic i.e. regular wave conditions and irregular wave test results obtained by spectral analysis, indicates that the identification methods of linear dynamic systems may be used for determining seakeeping qualities with respect to relative water motions on the ship's sides.
   In other words, the transfer functions obtained for deterministic conditions (either experimentally in regular waves or numerically) give a basis for predicting relative water motions in irregular waves.
3) The application of theoretically obtained relative motion transfer functions to the calculation of statistical exceedance parameters, sometimes gives results differing from those obtained directly from irregular wave model tests. The results are however comparable and the tendencies shown are as those shown by the majority of measured values. Taking into account the stochastic nature of the investigated process and the prognostic character of the computed exceedance parameters, the theoretical results can be accepted as being sufficiently correct for practical purposes.
4) The relative water surface motions on the weather side have a decidedly more intensive character. The magnitude of the variance of this process is governed by the heave and roll characteristics (and, of course, by the wave motion intensity).
   The variance for the lee side is considerably smaller because in this case only the region of roll resonance is the decisive factor.

Therefore the statistical characteristics of the exceedances for the weather side can be considered as a measure of the intensity of deck wetting. The lee side, on the other hand, is more relevant for investigations into the danger caused by the bulwark and deck edge submergence. The corresponding statistical characteristics for this side constitute a measure of the degree of immersion of the bulwark edge.

Considering that :

- the statistical characteristics of the exceedances, such as the probability of exceedance P_F, mean exceedance height $\overline{\Delta h}$ and mean exceedance period $\bar{\tau}$, which are in agreement with an intuitive physical interpretation, can be used to estimate the seakeeping qualities of a ship with respect to deck wetting and deck edge immersion of the leeward side;
- the previous conclusions confirm the correctness of the calculation of these parameters, for a given sea state, by theoretically obtained transfer functions;
- it is possible to develop the theoretical model presented herein for the case of a ship moving at any angle to the waves;
- there undoubtedly exists a connection between deck wetting and deck edge immersion, and the danger of stability loss;

the statistical characteristics of the water level exceeding the bulwark edge could be taken as one of the ship safety criteria.

The exceedance of certain maximum values of these parameters for certain weather conditions, would then be considered as endangering the stability of the ship.

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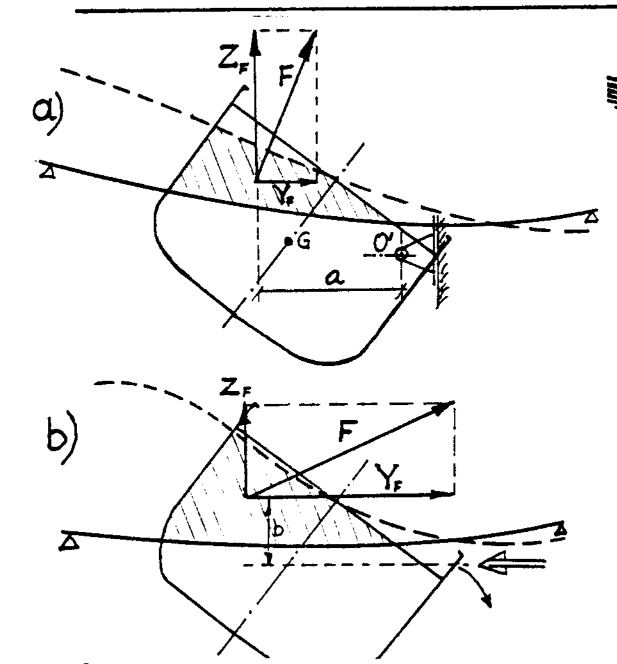


FIG. 1 THE SHIP WITH SUBMERGED BULWARK IN WAVES

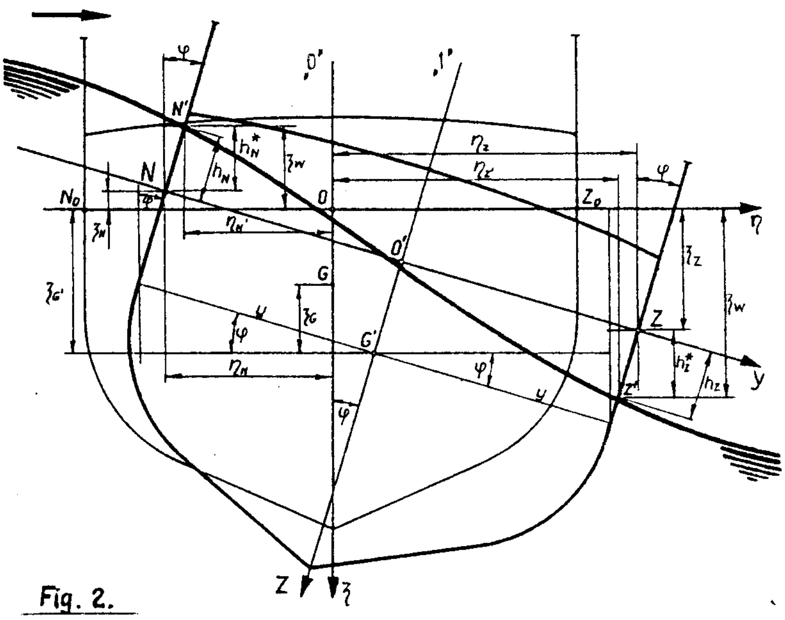


Fig. 2.
DETERMINATION OF THE FUNCTION OF WATER LEVEL OSCILLATIONS AT THE SHIP'S SIDE

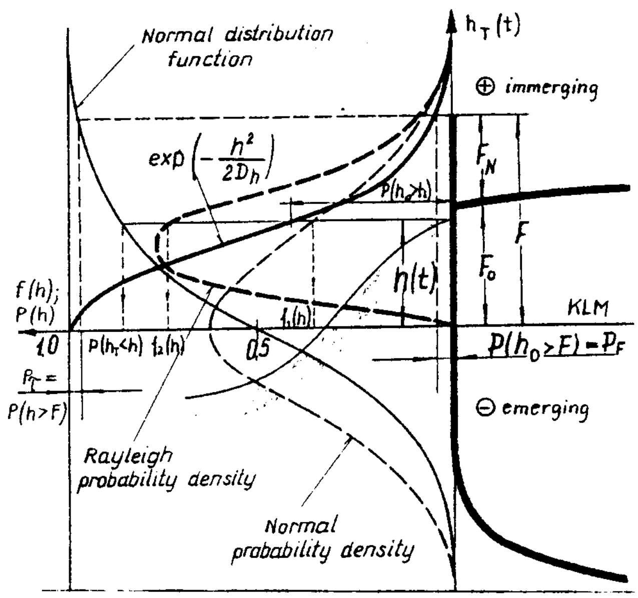


Fig.3 STATISTICAL CHARACTERISTICS OF WATER SURFACE OSCILLATION AT THE SHIP'S SIDE

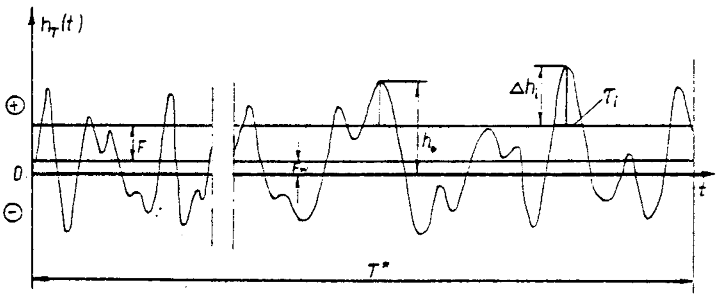
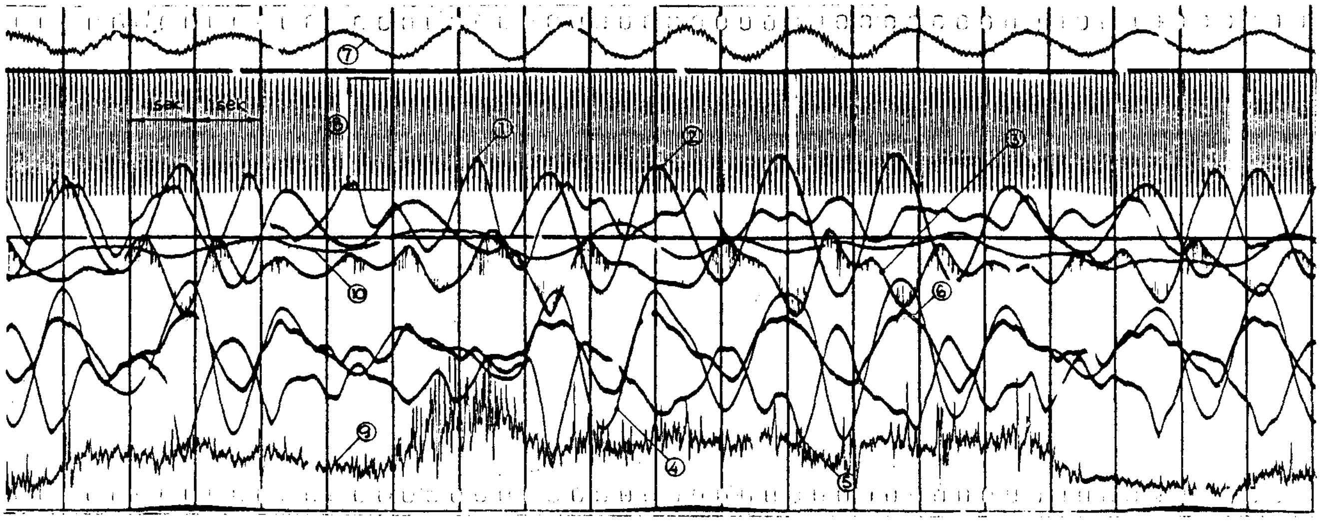


Fig. 4. The water surface oscillations at the ship's side as the random process.



① — Waves in the mobile system ($L_\eta(t)$)
② — Rolling ($\varphi(t)$)
③ — Heave acceleration in the mobile co-ordinates system ($\ddot{z}(t)$)
④ — Sway acceleration in the mobile co-ordinates system ($\ddot{y}(t)$)
⑤ — Water surface oscillations at the weather side ($h_N(t)$)
⑥ — Water surface oscillations at the lee side ($h_Z(t)$)
⑦ — Vertical acceleration of wave sounder ($\ddot{\zeta}(t)$)
⑧ — Mean wind velocity ($\bar{V}_w$)
⑨ — Instantaneous wind velocity ($V_w(t)$)
⑩ — Direction of the wind

Fig. 5. Fragment of the record tape of the experiments in natural wind beam waves.

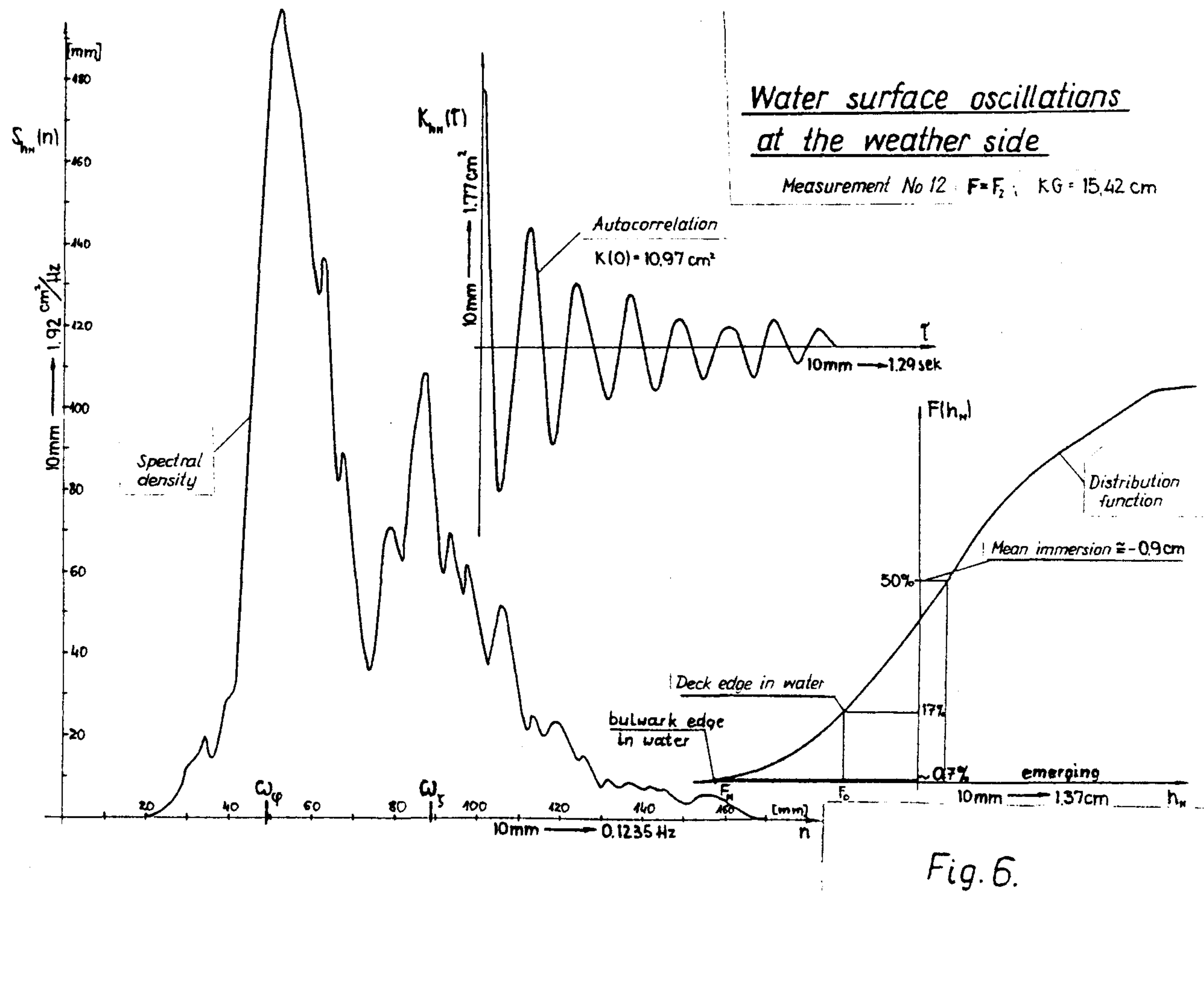


Fig. 6.

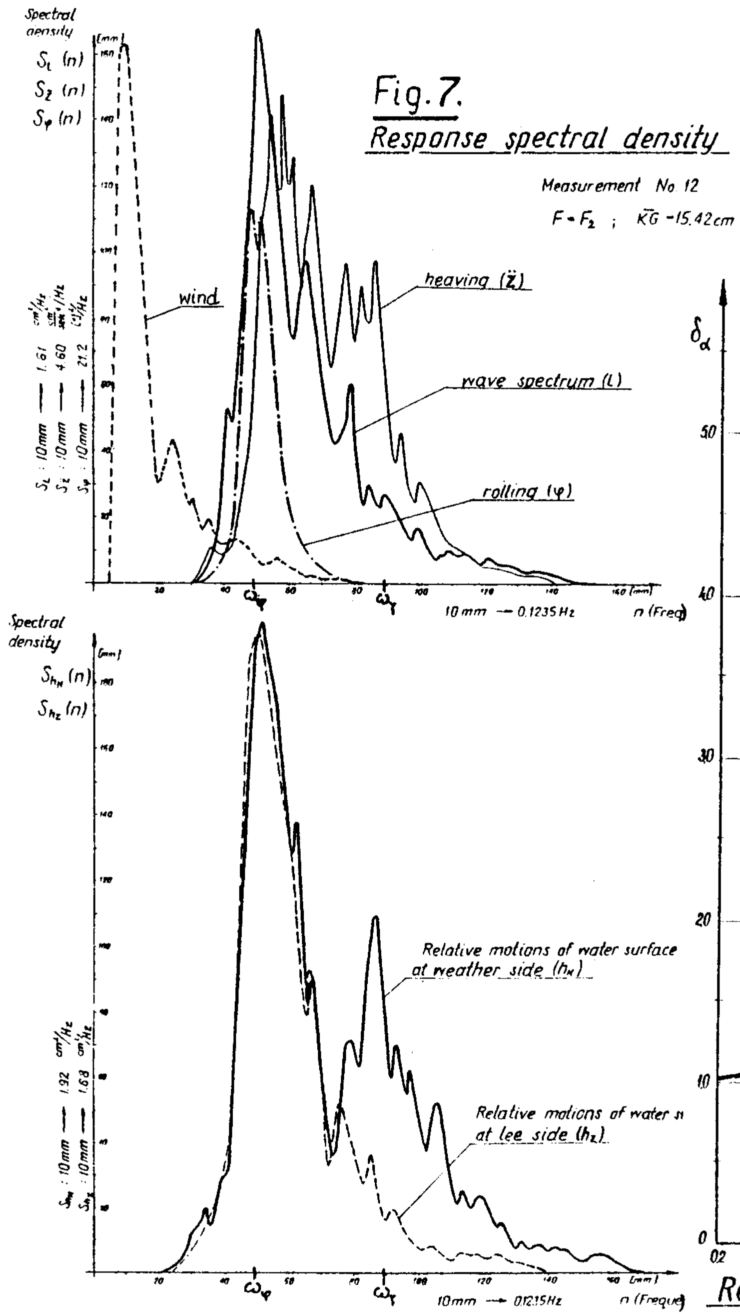


Fig. 7. *Response spectral density*

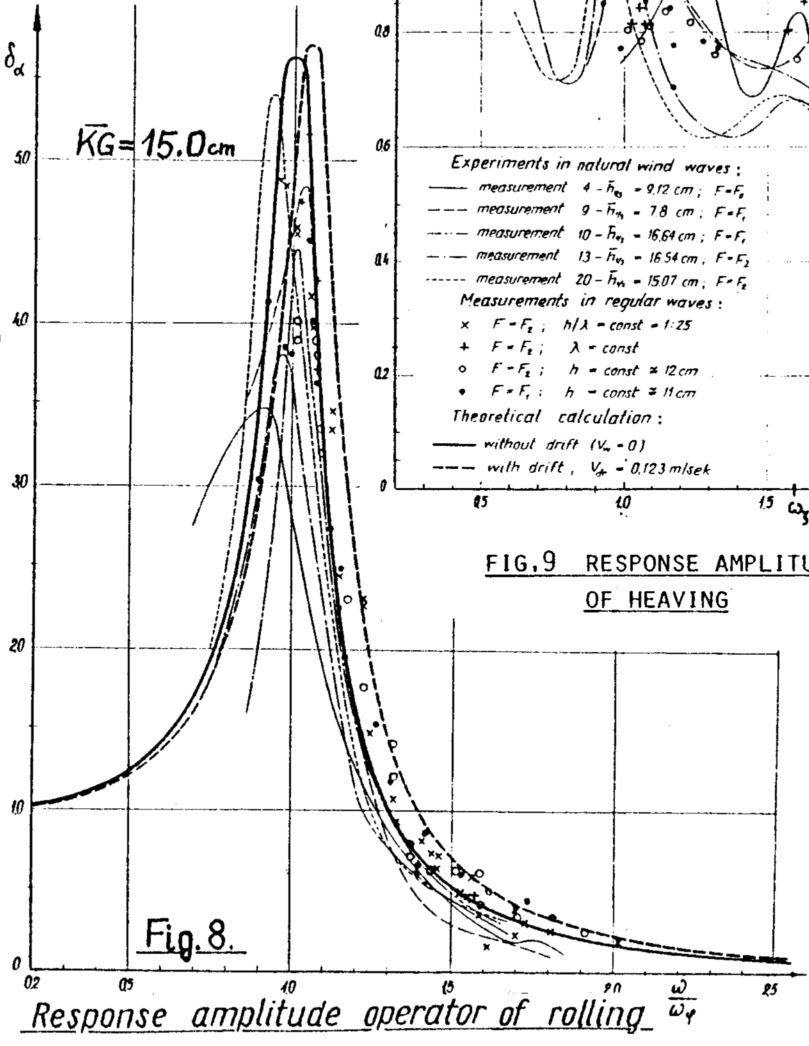


Fig. 8. *Response amplitude operator of rolling*

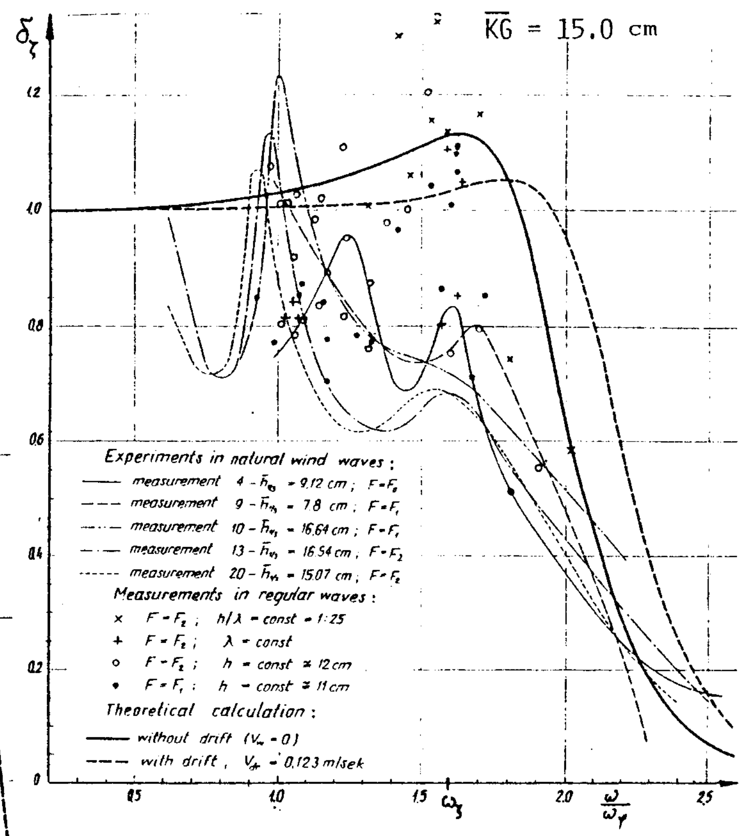


FIG.9 RESPONSE AMPLITUDE OPERATOR OF HEAVING

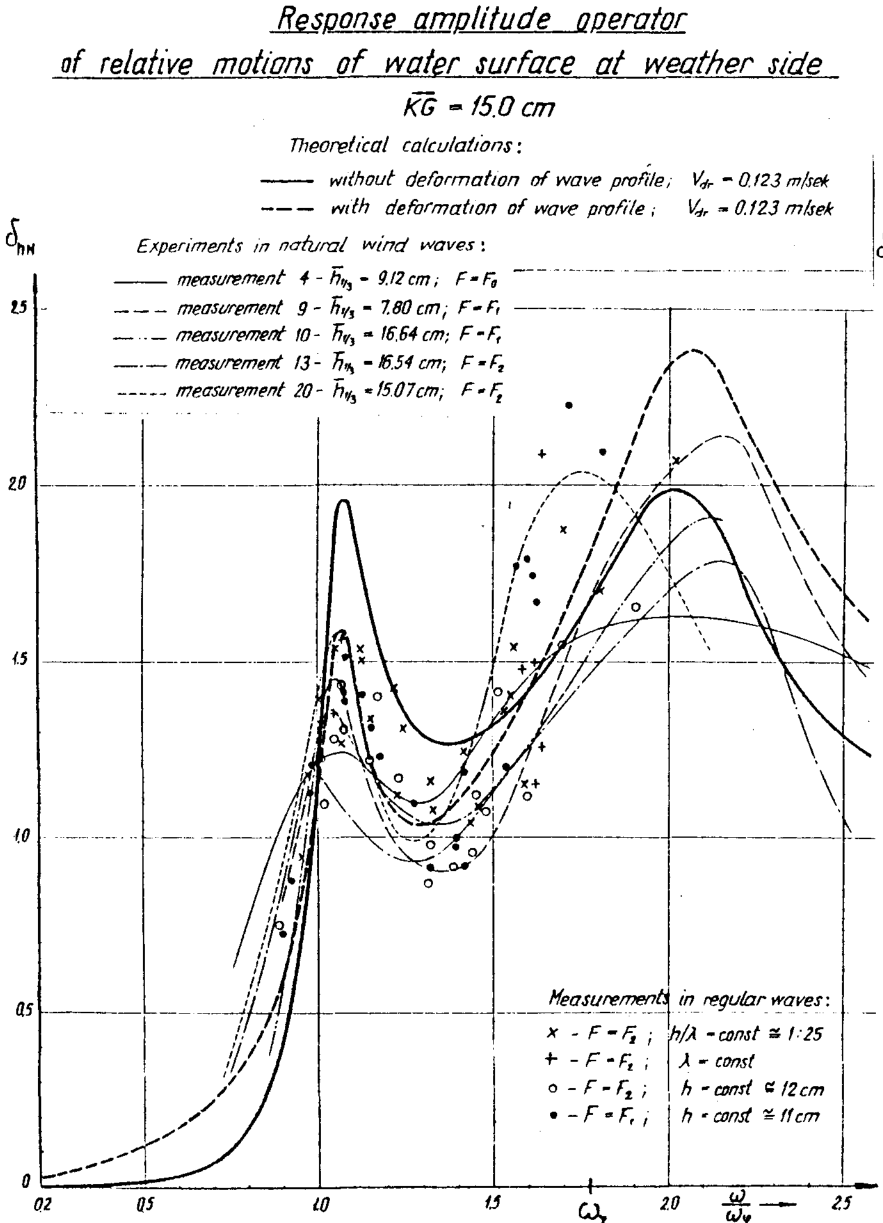

Response amplitude operator
of relative motions of water surface at weather side
$\overline{KG}$ = 15.0 cm
Theoretical calculations:
—— without deformation of wave profile; V_{dr} = 0.123 m/sek
– – – with deformation of wave profile; V_{dr} = 0.123 m/sek
Experiments in natural wind waves:
measurement 4 - $\bar{h}_{1/3}$ = 9.12 cm; F = F_0
measurement 9 - $\bar{h}_{1/3}$ = 7.80 cm; F = F_1
measurement 10 - $\bar{h}_{1/3}$ = 16.64 cm; F = F_1
measurement 13 - $\bar{h}_{1/3}$ = 16.54 cm; F = F_2
measurement 20 - $\bar{h}_{1/3}$ = 15.07 cm; F = F_2
Measurements in regular waves:
× - F = F_2; h/λ = const ≅ 1:25
+ - F = F_2; λ = const
○ - F = F_2; h = const ≅ 12 cm
● - F = F_1; h = const ≅ 11 cm
δ_{hM}
ω_ζ
$\frac{\omega}{\omega_\varphi}$
0
0.5
1.0
1.5
2.0
2.5
0.2
0.5
1.0
1.5
2.0
2.5

Fig. 10.

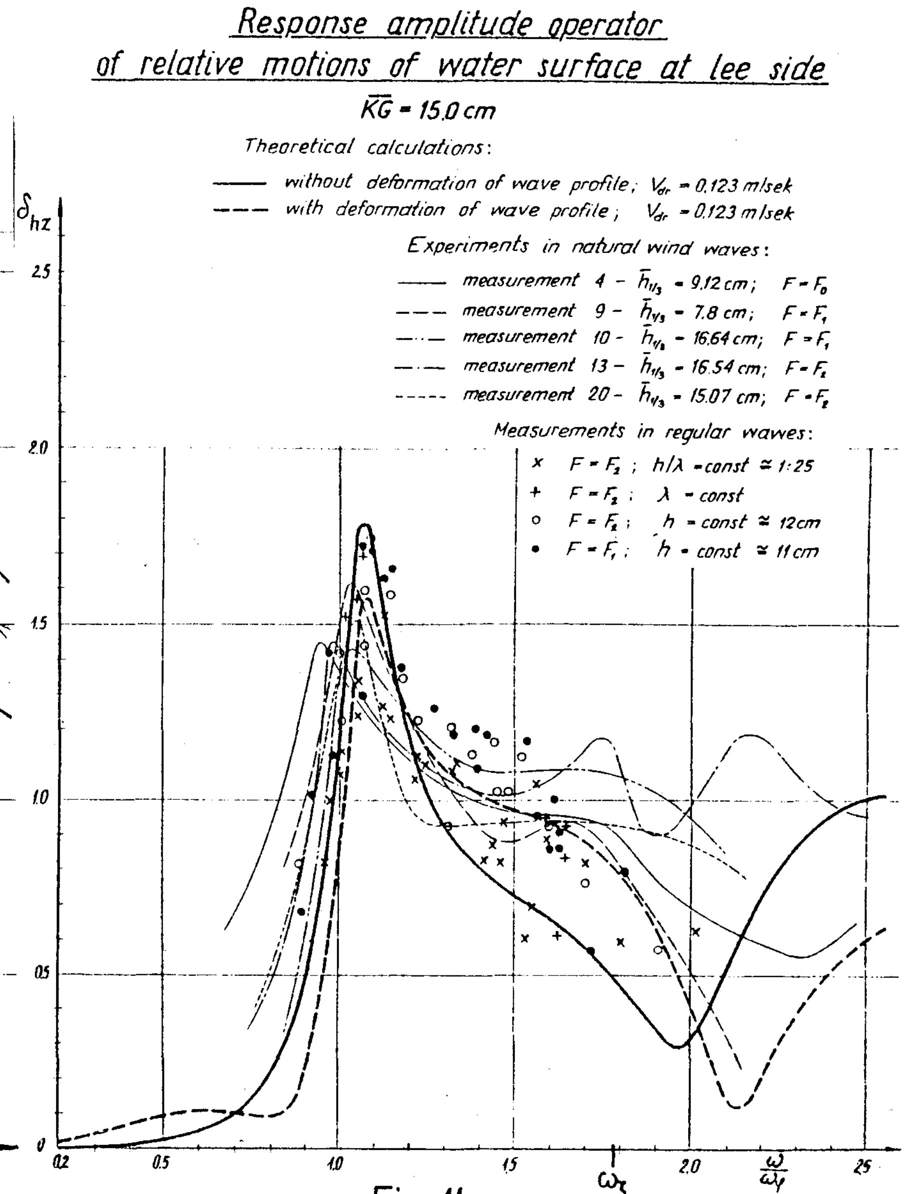

Response amplitude operator
of relative motions of water surface at lee side
$\overline{KG}$ = 15.0 cm
Theoretical calculations:
—— without deformation of wave profile; V_{dr} = 0.123 m/sek
– – – with deformation of wave profile; V_{dr} = 0.123 m/sek
Experiments in natural wind waves:
measurement 4 - $\bar{h}_{1/3}$ = 9.12 cm; F = F_0
measurement 9 - $\bar{h}_{1/3}$ = 7.8 cm; F = F_1
measurement 10 - $\bar{h}_{1/3}$ = 16.64 cm; F = F_1
measurement 13 - $\bar{h}_{1/3}$ = 16.54 cm; F = F_2
measurement 20 - $\bar{h}_{1/3}$ = 15.07 cm; F = F_2
Measurements in regular waves:
× F = F_2; h/λ = const ≅ 1:25
+ F = F_2; λ = const
○ F = F_2; h = const ≅ 12 cm
● F = F_1; h = const ≅ 11 cm
δ_{hz}
ω_ζ
$\frac{\omega}{\omega_\varphi}$
0
0.5
1.0
1.5
2.0
2.5
0.2
0.5
1.0
1.5
2.0
2.5

Fig. 11.

Response amplitude operator
of relative motions of water surface at weather side

$\overline{KG} = 15.42$ cm

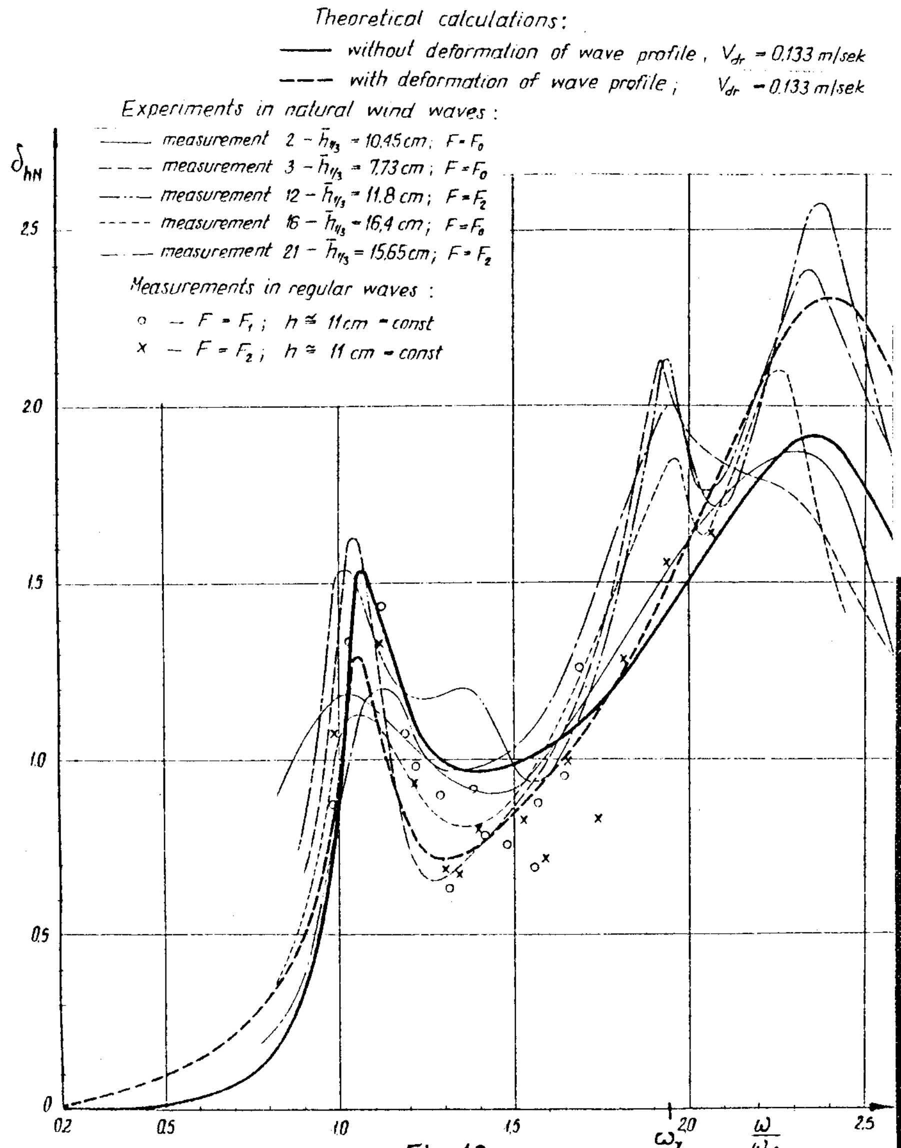
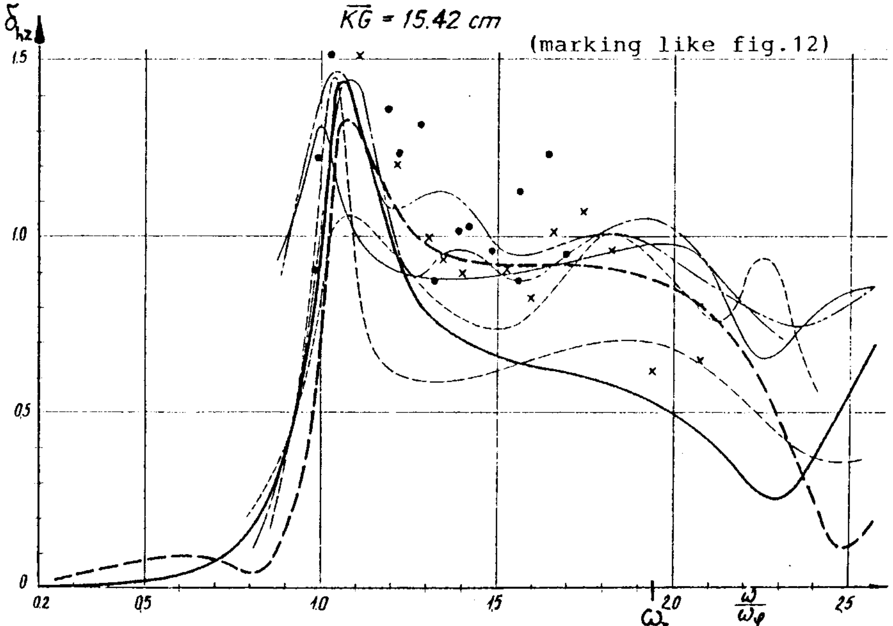
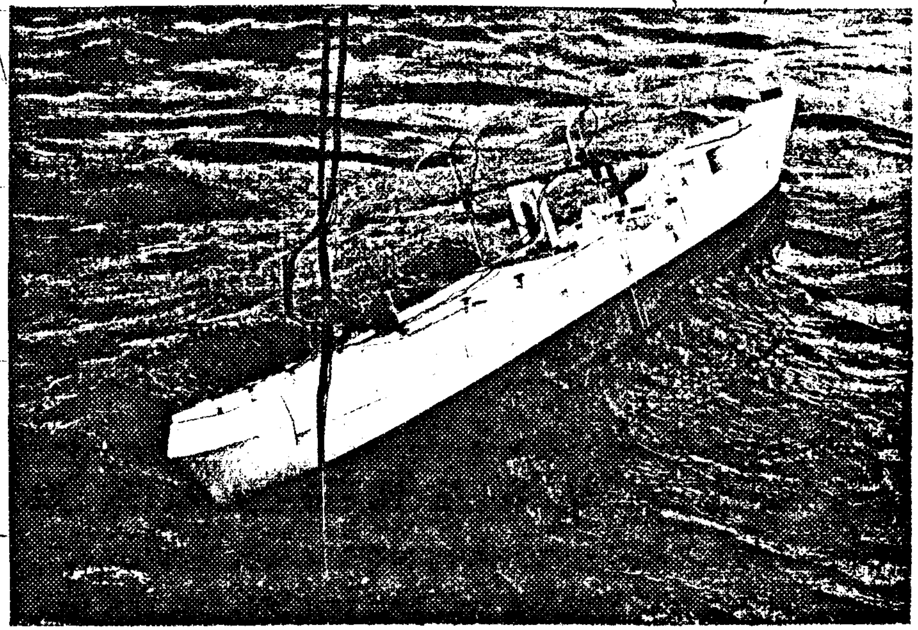


Fig.12.

Fig.13. Response amplitude operator
of relative motions of water surface at lee side

$\overline{KG} = 15.42$ cm





PHOT. 1 THE MODEL IN IRREGULAR WAVES ON THE LAKE

TAB. 1 THE STATISTICAL CHARACTERISTICS OF THE BULWARK EDGE EXCEEDANCE BY THE WATER LEVEL AT THE MODEL SIDE

Meas. No.	$\overline{KG}$ = 15.0 cm	Weather side							Lee side						
		D_h	$D_{\dot{h}}$	P_F	$\bar{n}_F$	P_τ	$\bar{\tau}$	$\bar{\Delta h}$	D_h	$D_{\dot{h}}$	P_F	$\bar{n}_F$	P_τ	$\bar{\tau}$	$\bar{\Delta h}$
		cm^2	$cm^2\,sec^{-2}$	%	sec^{-1}	%	sec	cm	cm^2	$cm^2\,sec^{-2}$	%	sec^{-1}	%	sec	cm
4	Calculated $\bar{A}_{\zeta,\zeta} = 0$	9.502	275.8	6.1	0.052	0.9	0.172	1.141	4.514	100.7	0.9	0.007	0.1	0.159	0.636
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	8.427	287.7	4.2	0.039	0.6	0.151	1.024	4.764	109.1	1.2	0.009	0.1	0.161	0.669
	Experiment	8.78	314.9	4.9	0.047	0.4	0.149	1.06	4.78	124.4	1.2	0.009	0.1	0.156	0.67
9	Calculated $\bar{A}_{\zeta,\zeta} = 0$	6.556	209.5	2.0	0.018	0.3	0.144	0.829	2.440	63.6	0.0	0.000	0.0	0.105	0.335
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	6.024	224.3	1.4	0.014	0.2	0.128	0.769	3.198	81.2	0.1	0.001	0.0	0.124	0.447
	Experiment	5.61	228.2	1.1	0.011	0.2	0.118	0.72	3.20	77.6	0.1	0.001	0.0	0.05	0.45
10	Calculated $\bar{A}_{\zeta,\zeta} = 0$	21.458	447.1	27.0	0.196	5.3	0.269	2.272	15.121	257.4	26.8	0.176	5.2	0.297	1.903
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	17.726	390.6	20.5	0.153	3.8	0.245	1.932	12.199	229.5	19.6	0.135	3.5	0.262	1.586
	Experiment	16.24	335.4	18.0	0.134	2.0	0.239	1.79	16.2	328.4	29.0	0.208	5.0	0.279	2.01
20	Calculated $\bar{A}_{\zeta,\zeta} = 0$	15.595	338.4	17.4	0.129	3.1	0.238	1.749	10.539	183.5	14.1	0.094	2.4	0.255	1.379
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	12.955	302.6	12.2	0.094	2.0	0.214	1.489	8.837	169.0	9.7	0.068	1.5	0.228	1.182
	Experiment	13.6	329.3	13.7	0.107	2.0	0.215	1.55	11.8	226.4	17.3	0.120	4.0	0.258	1.52
13	Calculated $\bar{A}_{\zeta,\zeta} = 0$	24.581	535.7	32.4	0.241	6.7	0.277	2.555	16.932	298.5	30.4	0.203	6.1	0.302	2.082
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	20.013	485.2	25.0	0.196	4.8	0.245	2.151	13.930	262.7	23.5	0.162	4.4	0.273	1.767
	Experiment	17.75	474.7	21.1	0.174	2.5	0.224	1.94	15.2	272.6	26.3	0.177	5.5	0.288	1.90
	$\overline{KG}$ = 15.42 cm	Weather side							Lee side						
3	Calculated $\bar{A}_{\zeta,\zeta} = 0$	4.820	187.8	0.5	0.005	0.1	0.113	0.619	0.987	35.4	0.0	0.000	0.0	0.000	0.000
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	5.460	237.1	0.9	0.009	0.1	0.113	0.695	2.075	61.1	0.0	0.000	0.0	0.056	0.176
	Experiment	5.6	241.0	1.0	0.010	0.1	0.120	0.72	1.39	46.7	0.0	0.000	0.0	0.000	0.000
2	Calculated $\bar{A}_{\zeta,\zeta} = 0$	8.636	255.3	5.0	0.043	0.7	0.166	1.060	3.535	75.2	0.2	0.002	0.0	0.145	0.500
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	7.783	286.0	3.6	0.035	0.5	0.143	0.965	5.229	111.7	1.5	0.011	0.2	0.170	0.719
	Experiment	8.5	259.3	4.9	0.043	0.7	0.163	1.05	5.06	122.3	1.3	0.012	0.1	0.137	0.70
16	Calculated $\bar{A}_{\zeta,\zeta} = 0$	15.257	277.9	13.7	0.093	2.3	0.248	1.651	10.669	152.2	18.3	0.110	3.3	0.297	1.462
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	12.244	243.4	8.4	0.060	1.3	0.219	1.360	10.643	173.2	18.2	0.117	3.3	0.278	1.459
	Experiment	14.1	355.0	11.8	0.094	2.0	0.207	1.55	9.3	145.7	14.1	0.110	3.0	0.218	1.300
12	Calculated $\bar{A}_{\zeta,\zeta} = 0$	9.834	241.9	5.5	0.044	0.8	0.185	1.145	5.212	92.0	2.4	0.016	0.3	0.196	0.751
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	8.227	246.5	3.1	0.027	0.4	0.156	0.975	6.436	121.9	4.8	0.033	0.7	0.206	0.909
	Experiment	10.97	297.5	7.6	0.056	0.6	0.207	1.27	7.9	133.2	8.2	0.052	1.8	0.250	1.09
21	Calculated $\bar{A}_{\zeta,\zeta} = 0$	14.095	237.6	12.5	0.082	2.1	0.253	1.559	10.263	142.3	15.9	0.094	2.8	0.293	1.393
	Calculated $\bar{A}_{\zeta,\zeta} \neq 0$	11.063	194.8	7.1	0.047	1.1	0.226	1.258	10.051	160.3	15.3	0.097	2.6	0.271	1.368
	Experiment	15.9	347.1	16.1	0.119	2.0	0.235	1.74	12.0	190.0	20.4	0.129	3.0	0.286	1.58