


Field Investigations of the Geometric Features of Wind Wave Breaking

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Abstract

Purpose. The paper is purposed at studying temporal variability of the geometric dimensions of wind wave breaking under natural conditions and at assessing the fraction of the sea surface covered with foam using the distribution of the breaking wave crest lengths.

Methods and Results. Field studies of the wave breaking characteristics were carried out from the stationary oceanographic platform located at 500 m off the Katsiveli coast (Black Sea hydrophysical subsatellite polygon). Geometric dimensions of wave breaking in the active phase and the velocity of wave movement were determined using video records of sea surface. Processing of video frame sequences has resulted in formation of the array of crest lengths, and the array of widths and areas of the varying in time foam structures. Meteorological information was obtained simultaneously with video records.

Conclusions. A connection independent of wind and wave conditions was established experimentally between the wave breaking geometric dimensions and the breaking wave length: the average width of breaking is proportional to the length of a breaking wave, the average area – to the squared length of a carrier wave. The values of these ratios are 0.03 and 0.002, respectively, that confirms the geometric similarity of wave breaking. It is shown that the length and width of an individual wave breaking increase at a constant rate, the value of which is conditioned by the scale of a breaking wave. The geometric characteristics of wave breaking normalized to the length of a breaking wave are linearly dependent on dimensionless time and independent of the scales and velocities of breaking waves. To calculate the fraction of sea surface covered with foam, the distributions of the wave breaking lengths were used. The field data values are shown to be adequately corresponding to the calculations by the model proposed by O. M. Phillips.

Keywords: wind wave breaking, field studies, distribution of breaking lengths, breaking similarity, fraction of the sea surface covered with wave breaking foam, growth rate of linear dimensions of breaking

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Introduction

Wave breaking at the sea surface is a complex hydrodynamic phenomenon. During its evolution, the foam structure goes through a whole range of intermediate states – from a breaker with a foaming crest to a disintegrating emulsion layer. According to [1, 2], two classes of foam formations can be fairly confidently



breaking is determined at $t = t_4$ (Fig. 3, *a*), when the value of the whitecap area reaches its maximum. At the same time, a mixed phase appears in the interval $t_3 < t \leq t_4$; during this time period the residual foam begins to separate from the whitecap (Fig. 2, *d*). As a result, the growth rate of breaking area decreases and at $t = t_4$ it becomes equal to zero, $\partial S^m(t)/\partial t|_{t=t_4} = 0$. The underestimated values of q powers in our case are due to the fact that the dependences $S^m(t)$ were approximated over the entire interval of the active phase of breaking $0 \leq t \leq t_4$, including the zone in the vicinity of the maximum area, where its variation rate is significantly lower and reaches zero.

Analysis of the data we obtained reveals that in the absence of a mixed phase in the interval $0 \leq t \leq (t_3 + t_4)/2$, the temporal variation of breaking area is satisfactorily described by the quadratic dependence (1). The study of temporal variability of the whitecap parameters in the transition phase requires more detailed additional research and is beyond the scope of this work.

Here, we are to describe temporal dependence of the whitecap area with the help of expression (2). Fig. 5 shows solid-colored lines denoting functions $S^m(t) = a^S t^2$ for selected velocity ranges.

The dependence of the obtained coefficients a^L , a^l and a^S on the average breaking velocity in the intervals $(c, c + \Delta c)$ is shown in Fig. 6, where the vertical segments correspond to the values of root-mean-square deviations $\pm \delta a^L, \pm \delta a^l, \pm \delta a^S$. The lines denote the dependences calculated by the least squares method: $a^L = (0.56 \pm 0.04)c$, $a^l = (0.19 \pm 0.01)c$, $a^S = (0.09 \pm 0.01)c^2$.

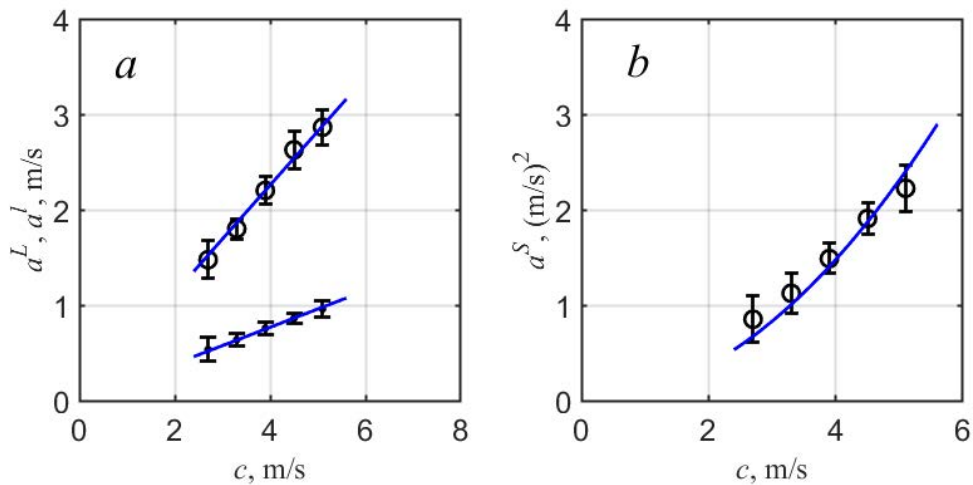


Fig. 6. Dependences a^L , a^l (*a*) and a^S (*b*) on the breaking wave velocity

The dependence of the obtained coefficients a^L , a^l and a^S on the average breaking velocity in the intervals $(c, c + \Delta c)$ is demonstrated in Fig. 6, where the vertical segments correspond to the values of root-mean-square deviations $\pm \delta a^L, \pm \delta a^l, \pm \delta a^S$. The lines denote the dependences $a^L = (0.56 \pm 0.04)c$, $a^l = (0.19 \pm 0.01)c$ and $a^S = (0.09 \pm 0.01)c^2$ calculated by the least squares method.

Considering the obtained functional dependencies of a^L , a^l , a^S coefficients, expressions (1) and (2) will be written in the following form:

$$\begin{aligned} L(t) &= (0.56 \pm 0.04)ct, \\ l(t) &= (0.19 \pm 0.01)ct, \end{aligned} \tag{3a}$$

$$S(t) = (0.09 \pm 0.01)c^2t^2. \tag{3b}$$

As the field data analysis showed, the whitecap linear dimensions increase at a constant rate, the value of which is determined by the breaking wave scale. At the same time, the whitecap area increases with time according to quadratic law and the growth rate S is proportional to c^2 .

We introduce dimensionless values $L'(t') = L(t)/\lambda$, $l'(t') = l(t)/\lambda$, $S'(t') = S(t)/\lambda^2$, $t' = t/T$. Then expressions (3a) and (3b), with account for the obvious relation $c = \lambda/T$, can be written down as

$$\begin{aligned} L'(t') &= 0.6t', \\ l'(t') &= 0.2t', \end{aligned} \tag{4a}$$

$$S'(t') = 0.1(t')^2. \tag{4b}$$

It follows from expressions (4) that evolution of the whitecap dimensionless geometric magnitudes in the active phase does not depend on the scale of the breaking waves.

The verification of the last statement is of interest. Indeed, semi-empirical dependences (4) were obtained for all values of c . We are to consider how significant the differences in the functions in formulas (4) will be at different velocities of breaking movement. Fig. 7 presents the variations by t' of the dimensionless length, crest width and dimensionless area of the whitecaps lying in the above-mentioned intervals ($c, c + \Delta c$). Solid lines in Fig. 7, $a - c$ indicate the dependences $L'(t') = a^{L'}t'$, $l'(t') = a^{l'}t'$, $S'(t') = a^{S'}(t')^2$ respectively, where the values of $a^{L'}$, $a^{l'}$, $a^{S'}$ coefficients were obtained by the least squares method. The color of the lines corresponds to the velocity range ($c, c + \Delta c$) (see explanatory notes). The colored areas in Fig. 7 show the areas where the values $L'(t') \pm \delta L'(t')$, $l'(t') \pm \delta l'(t')$ and $S'(t') \pm \delta S'(t')$ respectively, are located.

As follows from Fig. 7, a, b , the data $L'(t')$ and $l'(t')$ are grouped into dependences which are close to linear ones, with slopes of ~ 0.6 and ~ 0.2 , respectively, for all values of the breaking wave velocity, which is consistent with the coefficients in formula (4a). Dependences of breaking areas on dimensionless time for selected c , demonstrated in Fig. 7, c , are also close and group around $S'(t') = 0.1(t')^2$, which coincides with expression (4b).

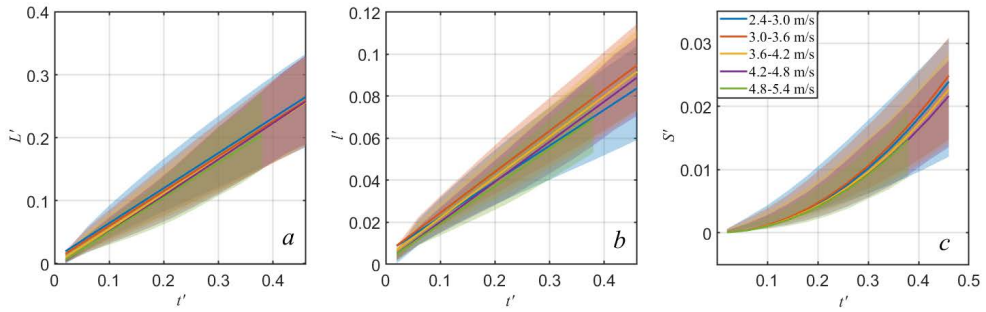


Fig. 7. Dependence of the dimensionless length (*a*), width (*b*) and area (*c*) on the dimensionless time. Solid lines correspond to the dependences obtained in the velocity intervals indicated in the legend

Fraction of foam-covered sea surface as a function of breaking length distribution. The fraction of the sea surface covered with breaking wave foam, W , is one of the main indicators of the dynamic processes of atmosphere – ocean interaction. In [5], it was proposed to use the distribution of wave crest lengths $\Lambda(\mathbf{c})$ as a statistical measure of wave breaking. The integral $\int \Lambda(\mathbf{c}) d\mathbf{c}$ is equal to the total length of the breaking crests per unit area of the sea surface. According to [5], at the moment of a whitecap generation, a foam zone appears which is formed by the moving breaking front and stays throughout the entire τ_p lifetime; in this case the total fraction of the foam-covered sea surface is written as

$$W = \int c\tau_p\Lambda(\mathbf{c})d\mathbf{c}. \quad (5)$$

On the other hand, when carrying out field studies, the breaking area S is recorded. When moving and increasing in dimensions, the whitecap does not leave visible bubbles behind and, as follows from Fig. 2, *a – d*, the surface behind the breaking is free of residual foam during the active phase. Then we should expect that the fraction of the sea surface W_E occupied by whitecaps will be less than W calculated by equation (5). We write down this equation for the fraction of the foam-covered sea surface in the active phase in the following form:

$$W_A = c_a \int c\tau\Lambda(\mathbf{c})d\mathbf{c}, \quad (6)$$

where c_a is a coefficient indicating that the foam zone area in the active phase is less than the total foam content of the sea surface ($\tau_p = \tau$ for the active phase). The justification for calculating W_A using expression (6) is presented in the Appendix. When calculating the non-Bragg scattering component in [7, 13], an expression similar to formula (6) was applied; c_a coefficient in these works was estimated by the correspondence of model calculations of the non-Bragg scattering component to field data.

Let us compare W_E values measured in the experiment and W_A calculated by formula (6) on the basis of the same database. W_E values were determined as

the average area of recorded breakings per unit of sea surface, which is a traditional method applied in numerous experimental studies:

$$W_E = \sum_i S_i / (AN_{fr}),$$

where A is a viewing area of the sea surface; N_{fr} is number of video frames. The duration of video recordings from which W_E was calculated varied within 20–30 min range.

The calculation of W_A values using field data was carried out as follows. According to the results of our measurements, one-dimensional distribution $\Lambda(c)$ was estimated as $\Lambda(c) = \frac{1}{A \cdot \Delta c \cdot N_{fr}} \sum_k L_k |c_k \in [c, c + \Delta c]$, where Δc is the velocity interval, in our case equal to 0.5 m/s; L_k is the length of the k -th crest of breaking wave moving at c_k velocity within the interval $c_k \in (c, c + \Delta c)$.

According to [9, 21], $\tau = \gamma_\tau T$, where γ_τ is proportionality coefficient; $T = \frac{2\pi}{g} c$ is breaking wave period. Based on the foregoing, we write down expression (6) for W_A in the following form:

$$W_A = c_a \frac{2\pi\gamma_\tau}{g} \int c^2 \Lambda(c) dc. \quad (7)$$

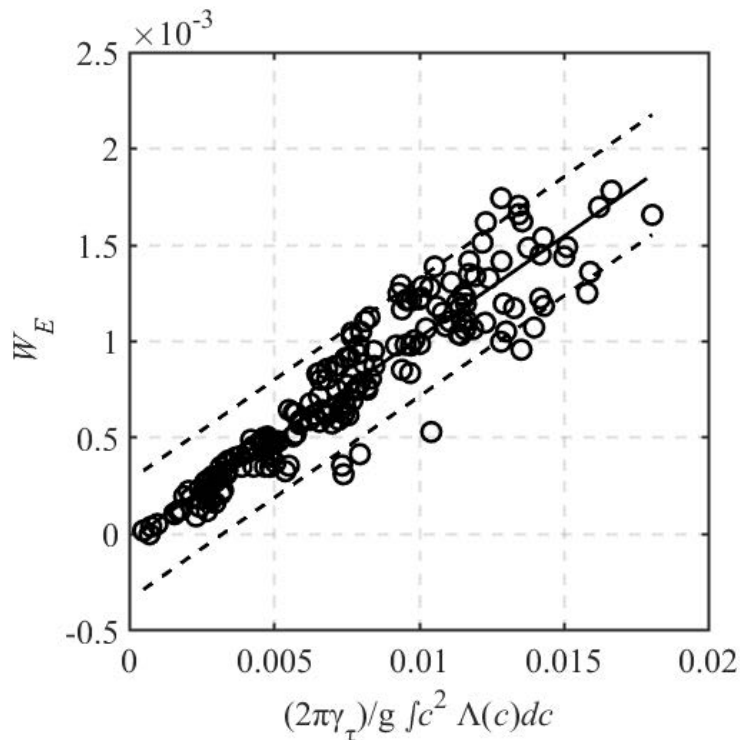


Fig. 8. Fraction of the sea surface covered with foam of breaking waves as compared to $\frac{2\pi\gamma_\tau}{g} \int c^2 \Lambda(c) dc$ (solid line is the data approximation by linear dependence, dashed lines are 95% confidence intervals)

Now we are to estimate the value of c_a coefficient. Fig. 8 gives a comparison of W_E and $\frac{2\pi\gamma_\tau}{g} \int c^2 \Lambda(c) dc$, where in accordance with [9] $\gamma_\tau = 0.33$; a solid line indicates the dependence $W_E = c_a \frac{2\pi\gamma_\tau}{g} \int c^2 \Lambda(c) dc$, where the value $c_a = 0.11 \pm 0.01$ was obtained by the least squares method.

Thus, expression (5) can be used with regard to the correction factor c_a in the models, when calculating the fraction of the sea surface covered by breakings in the active phase.

Conclusion

The work presents the results of field studies of temporal evolution patterns of geometric characteristics of gravitational wave breaking. Determination of breaking dimensions in the active phase and velocity of their movement was carried out using video recordings of the sea surface.

It has been experimentally shown that the average values of the whitecap width are linearly related to the breaking wave length $\bar{l} = 0.03\lambda$ and average areas of breakings are proportional to the square of the breaking wave length $\bar{S} = 0.002\lambda^2$. The relationships we found complement the results obtained earlier by the authors ($\bar{L}/\lambda \cong 0.1$ and $\bar{\tau}/T = 0.33$). Based on the experimentally obtained relationships for the crest lengths, minor axes, areas and lifetime in the active phase of breaking, which are constants, a conclusion on the geometric and kinematic similarity of breakings was drawn.

It has been experimentally shown that geometric dimensions of an individual whitecap (length and width) grow at constant rates and their values are determined by c : $a^l = (0.56 \pm 0.04)c$, $a^l = (0.19 \pm 0.01)c$. A quadratic dependence of growth of an individual breaking area on time has been established and the value of the leading coefficient is determined as $a^S = (0.09 \pm 0.01)c^2$.

The values of crest lengths and breaking widths normalized to the breaking wave length linearly depend on the dimensionless time $t' = t/T$, practically coincide and are grouped around the universal dependencies $L(t)/\lambda \cong 0.6t'$ and $l(t)/\lambda \cong 0.2t'$. The dependences of the areas normalized to λ^2 on t' are also close and grouped around $S(t')/\lambda^2 = 0.1(t')^2$. The obtained results enable us to speak about the independence of dimensionless geometric characteristics of breaking from breaking wave scale and velocities.

Calculations of the sea surface fraction covered with the foam of breaking waves were performed both in the traditional way (the average area of recorded breakings per unit of sea surface was calculated) and using statistics on the distribution of the breaking crest lengths.

A comparison of W_E with W values calculated using expression (7) showed a linear dependence $W_E = c_a \frac{2\pi\gamma_\tau}{g} \int c^2 \Lambda(c) dc$, where $c_a = 0.11 \pm 0.01$. Thus, one can use the expression for W proposed by O.M. Phillips, $W_E = c_a W$, in the developed models for describing sea surface. Taking into account the experimental estimates of a^l and γ_τ parameters obtained in this work, an explanation for the value of c_a coefficient is proposed.

Appendix

To estimate the model values of the sea surface fraction covered with active-phase breakings, we use the concept of $\Lambda(c)$ function proposed in [5]. Now we move on to a coordinate system with the origin at the foam structure center. We write down the variation of a single whitecap area over time dt as follows:

$$dS \cong dLdl, \tag{A1}$$

where dL, dl are increments in the breaking dimensions. According to expressions (1) and (2), $dL = a^l dt, dl = a^l dt$, and integrating equation (A1) over the breaking lifetime, we obtain an expression for the maximum whitecap area

$$S_m \cong a^l \tau L_m, \tag{A2}$$

where $L_m = a^l \tau$ is maximum length of breaking crest. Since, as shown above, $L(t)$ increases linearly from 0 to L_m , the average crest length is $\bar{L} = L_m/2$. According to the data in Fig. 5, $c, S(t)$ is described by a quadratic temporal dependence, and as a result, the ratio of the maximum area to its average value will be $\frac{S_m}{\bar{S}} = 3$. Using the relationships given here for the breaking lengths and areas, we rewrite expression (A2) for the average area of a single whitecap:

$$\bar{S} \simeq \frac{2}{3} a^l \tau \bar{L}. \tag{A3}$$

Summing up expressions (A3) for all breakings observed in area A , we obtain

$$\frac{1}{A} \sum_i \bar{S}_i \simeq \frac{2}{3A} a^l \tau \sum_i \bar{L}_i. \tag{A4}$$

Considering the fact that total breaking length per unit surface is $\int \Lambda(c) dc = \frac{1}{A} \sum_i \bar{L}_i$, and the left side in expression (A4) is the fraction of the sea surface W_A covered by the active phase of breaking waves, we rewrite expression (A4) in the following form:

$$W_A = 2/3 \int a^l \tau \Lambda(c) dc. \tag{A5}$$

The main difference between formula (A5) and equation (5) is that in the integrand (A5) the factor is not the whitecap movement velocity, but the growth rate of its minor axis a^l . According to the results presented above, $a^l = 0.2c$. Then

$$W_A = c'_a \frac{2\pi\gamma\tau}{g} \int c^2 \Lambda(c) dc,$$

where $c'_a = \frac{2}{3} 0.2 = 0.13$. The expression exactly coincides with formula (7), while c'_a and c_a values are close.

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Vladimir V. Malinovsky – development of experimental research method, analysis and synthesis of research results, participation in the discussion of paper materials, preparation of the paper text

The authors have read and approved the final manuscript.

The authors declare that they have no conflict of interest.