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Intensification of Nonlinear Wind Waves on Clean Water and in the Presence of an Oil Film

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Abstract—The intensification of gentle plane waves at the initial stage of their generation by a steady wind flow in a laboratory setup is investigated. It is found that the wave form is changed by eddies that are formed in the viscous layer of a steady air flow on the leeward slope: the water surface rises under the action of eddies to form a complexly shaped slope. Calculated and measured data for gentle nonlinear waves on clean water are in good compliance with each other. It is shown that, in the presence of an oil film, the region of eddy separation encompasses the wave trough as well, because oil flows down and the film is thickened in passing from the slope to the trough. The water-surface rise by eddies in the trough restricts an increase in the amplitude and steepness of the wave.

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INTRODUCTION

At the initial stage of wave generation by a horizontal air flow, short waves with parallel crests appear on the water surface. As long as the air-flow velocity is higher than the phase velocity of waves $u > c$, the amplitude, length, and phase velocity of waves increase. The intensification of waves is caused by a nonuniform distribution of the air pressure along the wave. Since the works of Kelvin (Jeffries, Shuleikin), this effect has been related to the formation of eddies on the leeward slope of the wave. A regular separation of eddies in the near-surface air layer on the leading (leeward) slope of a wave that is close to breaking is experimentally detected in [1]. The size of eddies is on the order of the wave amplitude. An intermittent air flow on the leading slopes of steep waves is investigated in greater detail in [2]. It is experimentally shown in [3] that the viscous layer in decelerating liquid flows periodically stops at the flat interface because of the friction force at the lower boundary of the layer and to the inverse pressure gradient at its upper boundary. Eddies that are formed inside the layer leave the layer after it stops. It is shown in [4] that these eddies control the turbulent characteristics of the boundary layer of the decelerating liquid flow. The velocity field and formation of eddy structures in a steady boundary layer of air over a gentle wave are experimentally investigated in [5, 6]. The pressure distribution along a linear wave is calculated in [5] with the aid of the Cauchy–Lagrange integral with allowance for the vertical velocity shear, disturbances produced by eddies, and a periodic deceleration of the viscous layer. The calculated growth rate of the amplitude of a linear wave corresponds to its experimental value. In order to describe the growth of nonlinear waves, it is necessary to solve a complex problem using numerical methods. Additionally, this approach makes it impossible to describe changes in the form of a gentle nonlinear wave observed during the experiment.

It is theoretically shown in [7] that the presence of eddies near the water surface distorts this surface: the water-surface band with a width approximately equal to two diameters of the eddy is displaced toward the eddy. The interaction time is estimated by the formula $\tau = \frac{\sqrt{D}}{\sqrt{g}}$, where D is the distance between the eddy and the water surface. It can be supposed that eddies forming in the air over the leading slope of the wave have a similar influence on the water surface. In this case, the form of a gentle nonlinear wave must be change. Experimental data on the boundary air layer and the process of eddy formation on the leeward slope of a wave [5, 6] make it possible to calculate the parameters of eddies and to estimate the wave deformation on the basis of the data obtained in [7].

The goal of this study is to experimentally verify this suggestion for the process of the intensification of gentle plane waves at the initial stage of their generation in a laboratory steady air flow on clean water and in the presence of an oil film, which substantially changes the roughness of the interface.

METHODS AND EQUIPMENT

These experiments were conducted in a transparent channel 3.5 m long, 50 cm high, and 20 cm wide. The height of the air channel over water was 10 cm. Waves were excited by a horizontal air flow which passed through a grate of horizontal cylinders installed at the inlet of the channel (Fig. 1). Deformations of the water surface were investigated with the aid of a video tape recording. The air-flow velocity was determined with an anemometer (a thermal resistor with a measuring head diameter of 0.2 mm served as a transducer). The anemometer was installed over a wave crest; the velocity was recorded for 1 min, whereupon the transducer was moved upward by 0.1 mm with a micrometric screw; and the recording was performed at the next horizon. The averaging was made for the maximum values over a wave period which corresponded to the passage of the crest. The intensity of velocity pulsations did not exceed 12% of the wind velocity fixed at a given horizon of the boundary layer. The vertical velocity profile obtained at a distance of 20 cm from the inlet is presented in Fig. 2. In the region of the maximum variance, the confidence interval of air-velocity measurements within the range $4.5 < u < 6.0$ m/s was 5 cm/s for a probability of 0.67. Fine foam-plastic particles were placed on the water surface. These particles were captured by the eddies that form in the viscous air layer and they allowed us to trace the trajectories of eddy structures.

At the beginning of the experiment, we recorded the process of intensification of waves on the surface of clean water. Then, this process was recorded under the same conditions on the water surface covered by a surfactant film with the thicknesses $w = 50$, 100, and 200 μm. In this experiment we used sunflower oil, which has the following characteristics at 20°C: the kinematic viscosity is 0.044 cm^2/s and the density is 0.9 g/cm^3.

INTENSIFICATION OF PLANE WAVES ON CLEAN WATER

It is experimentally shown in [3, 8] that, under the action of a horizontal decelerating air flow, a monochromatic wave appears on the water surface. The generation of this wave is accompanied by a periodic separation of cylindrical eddies whose horizontal axes are perpendicular to the flow direction. The eddies form at equal distances s along the longitudinal axis x and escape simultaneously with period T from the viscous air layer, thus producing periodical pressure drops at the escape points. The wavelength is equal to the distance between eddies.

The frame showing the water surface in the wave-generation zone is presented in Fig. 3. The plane waves with amplitudes increasing along the x axis are seen on the initial segment $x < 22.3$ cm (x is the distance from the channel inlet). Longer three-dimensional waves, which form during the breaking of the plane wave with a limiting steepness of $ak \approx 0.32$, appear on the water surface at $x > 22.3$ cm [9]. The

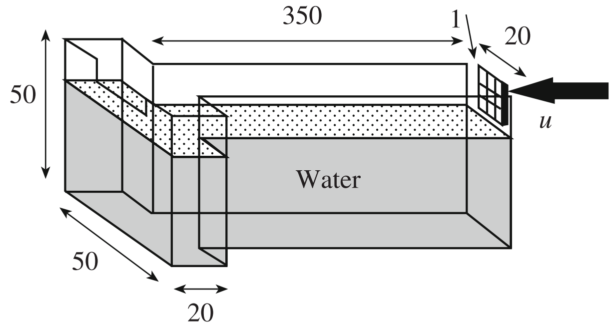

Fig. 1. Scheme of the setup.

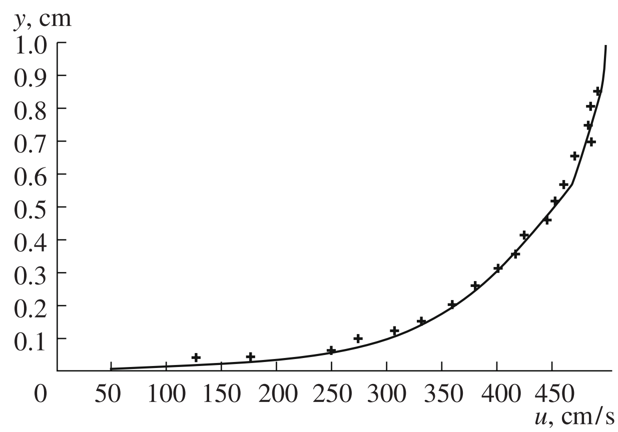

Fig. 2. Vertical velocity profile over a wave crest on the segment $x < 4$ cm.

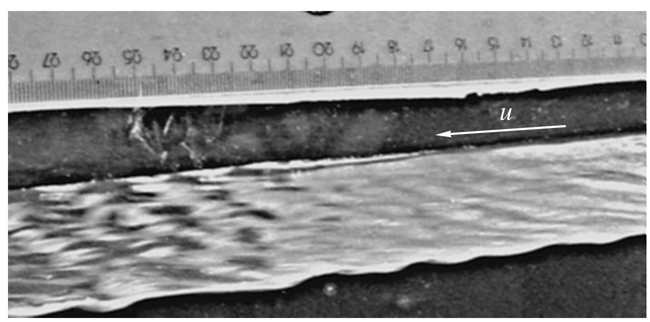

Fig. 3. Water surface in the zone of wave generation.

wind velocity at the channel inlet attains its maximum value $u = 5.6$ m/s at the height $h = 1$ cm over the undisturbed water surface. The viscous-layer thickness (linear vertical profile of the velocity) is $\delta = 0.05$ cm. On the initial segment $x < 4$ cm, the longitudinal velocity gradient at the height $h = 1$ cm is $u_x = -2.58$ s^{-1}. The escape of eddies is fixed in this zone by tracks of captured light particles (Fig. 4). The distance between

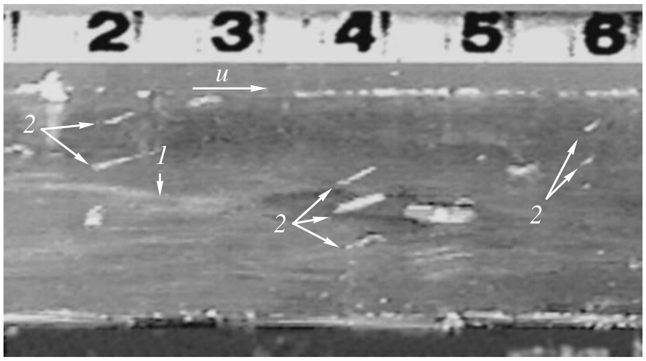

Fig. 4. Channel inlet. Tracks of particles captured by eddies that escaped from the viscous layer into the air: (*1*) water surface, (*2*) tracks; u = 5 m/s.

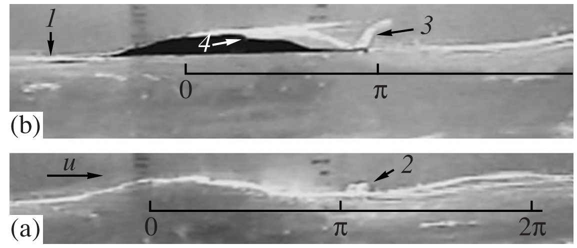

Fig. 5. Changes in the form of a nonlinear wave on clean water. Consecutive frames are taken at intervals of 0.04 s: (*1*) water surface, (*2*) particle on the water surface, (*3*) track of the same particle captured by the eddy that escaped into the air in a direction perpendicular to the water surface, (*4*) dark region repeats the shape of the crest in frame (a); u = 5 m/s, λ = 1.81 cm.

eddies s and the period of escape T are determined from the expressions [3]

$$s = Tu_s - \frac{\delta}{2C_f}\ln\left(1 + u_s\frac{2C_f}{|5u_x|\delta}\right), \quad (1)$$

$$T = \left(\frac{2\delta}{5u_s|u_x|C_f}\right)^{1/2}\operatorname{arctg}\left(\sqrt{\frac{2u_sC_f}{5|u_x|\delta}}\right),\ u_x = \frac{\partial u}{\partial x}, \quad (2)$$

where u_s is the mean velocity on the near-water streamline and $C_f = 0.01$ is the coefficient of sliding friction for air on the water surface at 20°C (numerically equal to the kinematic viscosity). For the specified range of wind-velocity variations, $u_s = u/10$ [3, 6]. Calculating the distance between eddies and the period of eddy escape with the use of (1) and (2) yields the values $s = 1.8$ cm and $T = 0.063$ s, which are close to the experimental data (Fig. 2). The generation of waves of the same wavelength is also observed in this region, which supports the conclusion of [7] that the generation of waves in a horizontal air flow is caused by the periodic separation of a vortex of eddies.

On the leading slope of the wave, the velocity of the air flow moving along the wave decreases in the direction of motion, which results in the formation of a system of eddies in the viscous air layer. According to [3, 5, 6], the radius of eddies is $r = \delta/3$ and the distance between the eddy center and the water surface is $D = r$. Calculating the eddy parameters s and T by (1) and (2) with the use of the assumption that, for $\tau < T$, each eddy displaces the water-surface band with the width $4r$ by the distance r in a direction perpendicular to the water surface, we can determine the consecutive changes in the wave form during each separation of eddies. In the given experiment, the eddy radius was $r = \delta/3 \approx 0.017$ cm, $\tau = 0.001$ cm, the minimum T value was $\approx$0.004 s, and the condition $\tau < T$ was fulfilled.

For calculating the eddy parameters, we measured the distribution of the wind velocity $u(x)$ at the height $y = h$, where h is the coordinate on which the maximum wind velocity is observed (coordinate origin is on the wave crest). The measurements showed that, for the small-amplitude waves under investigation, $u(x)$ can be approximated by the expression $u(x) = U_0h/f(x)$, where U_0 is the wind velocity at the height $y = h$ over a wave crest and $f(x)$ describes the water surface in the coordinate system related to the wave. This function is determined from a video record. Within the range of wind velocity variations on the segment under investigation ($x < 23$ cm), $4.5 < u < 5.6$ m/s; the main parameters are as follows: $h = 1$ cm, $u_s = u(x)/10$, and $\delta = 0.05$ cm; the longitudinal velocity gradient was calculated along the tangent to the wave surface.

Figure 5 shows the change in the form of a nonlinear wave of a small steepness with $ak = 0.2$ in the two consecutive frames taken with the time interval $\Delta t = 0.04$ s at the distance $x = 19$ cm from the channel inlet. No wave deformations are observed on the rear slope, in the trough, or on the peak of the wave. The leading slope of the wave is deformed, and the deformation is maximum in its middle. This phenomenon agrees with the proposed model, because eddies only form in a decelerating flow on the leading slope and the longitudinal velocity gradient is maximum in the middle of this slope, which corresponds to the highest frequency of the escape of eddies. The escape of eddies is fixed by tracks of light particles captured by eddies from the water surface at the instant of their formation.

Displacing the water surface in the perpendicular direction, eddies at the crest increase the wave height. During each subsequent escape, these eddies displace the wave crest in the direction of motion, because a positive slope of the water surface (positive longitudinal velocity gradient) arises between the first eddy and the wave crest, and eddies do not form. In the lower part of the slope, eddies displace the water surface upward and forward, thus increasing the wavelength. The middle part of the slope rises more rapidly than the crest, which, at a certain stage, leads to the formation of two small crests and a horizontal step between them (Fig. 5a). A further rise of the leading small crest

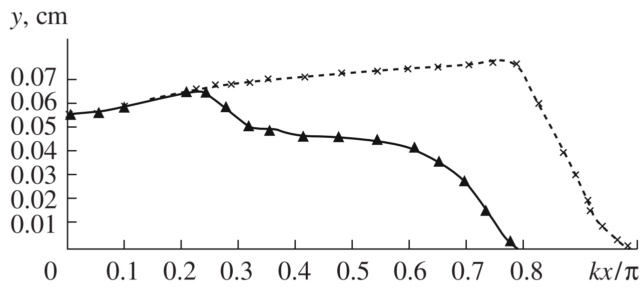

Fig. 6. Changes in the wave form that are obtained as a result of calculations.

forms a wave with a steeper leeward slope (Fig. 5b). The calculation of changes in the wave form that are caused by eddies is presented in Fig. 6. This calculation reflects all the deformation features of a gentle wave that were observed during the experiment.

The parameters of the wave and eddies (on the top of the slope) for four consecutive frames are given in Table 1. These data make it possible to compare the calculated and experimental values for small-amplitude plane waves in the entire range of wave steepness values: a is the wave amplitude in the frame, a_{calc} is the calculated amplitude, $u = 5$ m/s, t is time, x is the distance from the channel inlet, c is the phase velocity of the wave, and $k = \dfrac{2\pi}{\lambda}$.

In the specified range of x values, the nonlinear wave is plane. In the last frame, the wave steepness is close to its limiting value $ak = 0.32$, at which plane waves lose their stability and decay into longer three-dimensional waves. Such waves are seen in Fig. 1 for $x > 22.3$ cm. The calculated and experimental data given in this table differ by values lying within the confidence interval of determining the wave amplitude (0.004 cm for a probability of 0.67). Although the calculation correctly describes changes in the amplitude of a steep wave, nevertheless, changes in the form of waves whose steepness exceeds the value $ak = 0.27$ cannot be described exactly; this is evidently due to the interaction of nonlinear modes. Additional distortions of the wave form can be expected for large-amplitude steep waves that are affected by an intermittent air flow which forms eddies whose sizes are on the order of the wave amplitude [1, 2].

INTENSIFICATION OF WAVES ON WATER WITH AN OIL FILM

Oil spreads over the water surface, forming a thin film whose thickness is close to the length of the oil molecule (about 2.5 nm). The thickness of a monomolecular film depends on the position of an oil molecule with respect to the water surface: the short positively charged hydrophilic part of the molecule interacts with molecules of water bound by hydrogen bonds, whereas the long hydrophobic part rises above water. The influence of an insoluble surfactant film on the intensity of nonlinear interaction between the harmonics of a periodic traveling wave on the surface of a charged liquid is considered in [10], where it is shown that the presence of a surfactant film increases the resonance wave number at which the nonlinear interaction of waves is most intense. The results of the cited study suggest that the presence of an oil film on the water surface must substantially alter the process of intensification of wind waves, which depends on the nonlinear interaction of harmonics. This suggestion was checked experimentally in the cited study, because there is currently no physical theory of this phenomenon.

In our experiments we first investigated the process of wave intensification on clean water. After that, without setup shutdown, we investigated this process in the presence of an oil film, which allowed us to compare the data of experiments performed at the same external parameters. When the oil film was added, the longitudinal velocity gradient increased with the film thickness, which corresponded to an increase in the coefficient of friction of the air flow against the oil surface, which is proportional to the viscosity of the liquid. The generation of waves was observed on the initial segment of a 5-cm-long channel at a wind velocity of 4.3 m/s. The dependences of the wavelength, the longitudinal velocity gradient ($x < 5$ cm), and the friction coefficient on the film thickness w are presented in Table 2.

In the wave-generation zone, the wavelength decreases as the thickness of the oil film increases and it corresponds to the calculations that use formulas (1) and (2). The ratio of the friction coefficients for a 200-μm-thick film and clean water $C_f^{200}/C_f = 4.4$ is close to the ratio of the kinematic viscosity values for sunflower oil and clean water at 20°C.

Table 1

Frame	t, s	x, cm	c, cm/s	λ, cm	ak	T, s	s, cm	a, cm	a_{calc}, cm
1	0	18.5	28.5	1.80	0.195	0.007	0.18	0.056	
2	0.04	19.7	30.5	1.81	0.232	0.006	0.15	0.066	0.065
3	0.08	21.0	33.0	1.86	0.270	0.006	0.15	0.080	0.082
4	0.12	22.3	35.8	1.91	0.309	0.005	0.13	0.094	0.093

Table 2

w, μm	$u_{x_{x=5\text{ cm}}}$, s^{-1}	C_f	λ, cm	λ_{calc}, cm
0	2.2	0.01	3.00	2.90
50	2.25	0.015	2.75	2.70
100	2.3	0.02	2.46	2.45
200	2.4	0.044	1.89	1.90

Wave-steepness variations along the x axis at different film thicknesses are shown in Fig. 7. It follows from the presented data that plane waves with a limiting steepness $ak \approx 0.31$ occur on clean water and at $w = 50$ μm; during these experiments, we observed the decay of a plane wave into three-dimensional waves. The growth rate of the wave steepness on the water surface covered by a 50-μm-thick film is higher than on clean water. This result is caused by the higher friction coefficient at the oil–air interface, which increases the longitudinal velocity gradient and the frequency of eddy escapes on the leading slope of the wave. The plane wave with a limiting steepness has a smaller wavelength (3.5 cm) on water covered by a film with $w = 50$ μm than on clean water (4.6 cm), which agrees with [10].

During the experiments with oil films that had thicknesses of $w = 100$ and 200 μm, no wave decay was detected. The maximum values of plane-wave steepness (0.17 and 0.19) were attained at distances of 30 and 60 cm from the channel inlet, respectively; the steepness decreased downstream (Fig. 7). The restriction of the wave-steepness growth is due to the fact that the wavelength increased monotonically (more rapidly than during the experiments on clean water), whereas the wave amplitude first increased very slowly and then dropped. Video recording showed that, in these experiments, the region of intense eddy separation not only extended to the leeward slope but also encompassed the wave trough (Fig. 8). The intense separation of eddies in the trough rises the water surface and decreases the wave amplitude.

The intense separation of eddies in the wave trough points to a high longitudinal gradient of the air velocity in the near-water layer. We can suggest that, on the wavy water surface, oil slides down from crests to form a thicker film in the troughs. This suggestion is supported by video which shows (in colored frames) dark regions in film ruptures on steep wave slopes. The film-thickness growth in passing from the slope to the trough increases the longitudinal velocity gradient of the air flow, because the friction coefficient increases with the film thickness. The described qualitative model for suppressing the wave growth by an oil film supplements the well-known hypothesis stating that this phenomenon is associated with the elasticity of surfactant films (see, for example, [11]).

CONCLUSIONS

It has been shown experimentally that the intensification and deformation of a nonlinear wave (small-amplitude and gentle) by the wind in the wave-generation zone are caused by the action of eddies that form in the air on the leeward slope of the wave in the viscous layer: the water surface is displaced in the direction of eddies, which leads to an increase in the wave amplitude and to the formation of a steep leading slope. In the presence of an oil film and at the growth of its thickness, the wavelength in the zone of wave generation decreases because the longitudinal velocity gradient increases, which is due to the increasing friction coefficient. For the $w = 50$-μm-thick film, the wave steepness grows more rapidly than on clean water, because the friction on the leeward slope increases, which intensifies the escape of eddies. If the film thickness increases, oil flows down from the wave slopes to form an inhomogeneous film in the troughs,

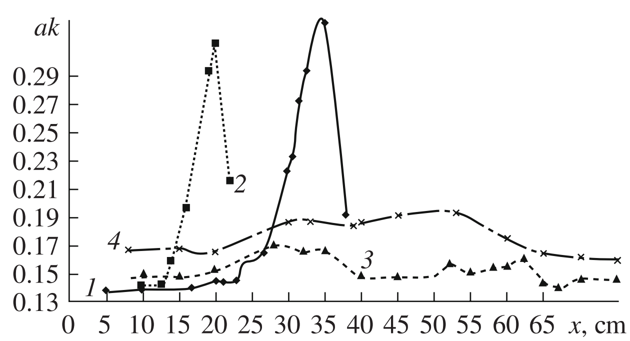

Fig. 7. Changes in the wave steepness along the x axis: (*1*) on clean water and at the film thickness w (*2*) 50 μm, (*3*) 100 μ, and (*4*) 200 μm; $u = 5$ m/s.

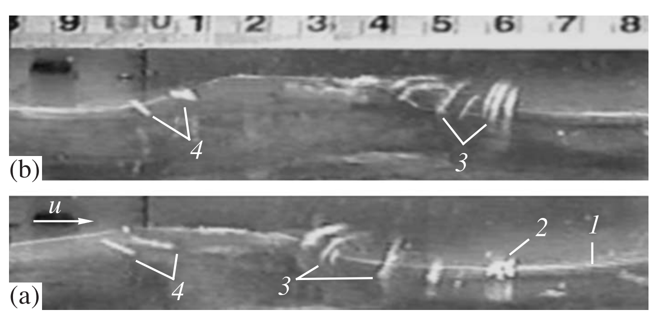

Fig. 8. Tracks of eddies escaping from the wave trough on water with the 100-μm-thick film: (*1*) water surface, (*2*) foam-plastic particles on the water surface, (*3*) tracks of particles captured by eddies that escaped during the exposure time, (*4*) tracks of particles captured by eddies flying toward water at the end of the trajectory; $u = 5$ m/s.

which leads to an increase in the longitudinal velocity gradient, an intense escape of eddies, and a rapid rise in the water surface. The rise of the water surface in the trough restricts the growth of the wave amplitude and steepness, ensuring an additional mechanism of wave attenuation by surfactant films.

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