Effect of a floating particles layer on breaking surface gravity waves

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Abstract. The results of experiments on the influence of a layer of particles of positive buoyancy on the suppression of the breaking process and the regularization of a standing gravity wave on a free surface of water in a rectangular vessel are discussed. The oscillations of a two-layer system in a barotropic mode are considered. Parametric resonance is used to excite the waves in a rectangular vessel. The effect of increase in the upper layer thickness on the limit steepness of the regular wave and its dissipative properties are considered. It is shown that the use of floating polystyrene particles as the upper layer changes significantly wave mode dynamics, namely, regularization of waves with complete suppression of breaking mechanisms.

1. Introduction

It was experimentally established that the regularization of breaking standing gravity waves on the free surface of water in a rectangular vessel is achieved by the following two methods.

Firstly, instead of water, one can use a viscous liquid, for example, seed oil. When the kinematic viscosity of the working liquid exceeds the threshold value, waves are regularized in the complete absence of their breaking [1, 2]. The mechanism of viscous regularization of wave motion observed in experiments was associated with the presence of a short-wave cutoff region where viscous dissipation becomes the dominant factor and short-wave disturbances responsible for the breaking of the standing wave are suppressed.

The second method consists in regularizing the breaking gravity waves on the free surface of the water with a layer of a lighter (immiscible with water) viscous liquid [3, 4]. In this case, the wave motion of the two-layer system occurs in a barotropic mode – oscillations the free surface and the interface of the two-layer system occur in phase. The experiments showed that the suppression of the mechanism of destruction of standing waves is determined by the emulsion formed during intense vibrations of immiscible liquids.

The study [5] on the dynamics of wind waves in the marginal ice zone of the ocean showed intense wave dissipation in the presence of grease ice or a layer of small ice floes on the ocean surface. To reveal the nature of this attenuation, the experiment [6] was recently conducted, in which grease ice...
was modeled by a layer of floating spherical particles. Based on the results of this laboratory study, a conclusion was drawn about the determining dissipative effect of the particle layer on the lower mode of the gravity standing wave in a rectangular vessel. Since the wave motions in [6] were created during a quick single translation of the initially inclined vessel into a horizontal position, the effect of particles on the mechanism of standing wave breaking was not studied.

The purpose of this work is to study the effect of a layer of spherical particles of positive buoyancy on the suppression of the breaking process and the regularization of standing gravity surface waves. In experiments, a layer of floating particles was placed on the free surface of salty water and this two-layer system oscillates like a homogeneous fluid, which refers to the barotropic mode of oscillations.

The subject of the study is related to solving practical problems of suppressing intense oscillations of a liquid with a free surface in the form of standing gravity waves.

2. Experimental procedure

The effect of the layer of floating particles on liquid sloshing was studied for the second mode \((n = 2)\) of standing gravity waves on a free surface of the dispersed system – a layer of concentrated suspension of particles and dispersion liquid – in a rectangular acrylic vessel with a length of \(L = 50\) cm and a width of \(W = 4\) cm.

The vessel was placed on the platform of an electromechanical shaking table providing harmonic oscillations in a vertical direction. Two-dimensional wave motions were investigated in the regime of the main Faraday resonance [1-4], when the vessel oscillation frequency \(\Omega\) is twice the frequency \(\omega\) of excited waves \((\Omega \sim 2\omega)\). With fixed vessel amplitude \(s = 0.75\) cm the variations of \(\Omega\) provided a change in the wave steepness \(\Gamma = H/\lambda\) within 0.005 – 0.5 at a wavelength of \(\lambda = 50\) cm, where \(H\) is the wave height. The range of overload changes \(\epsilon = s\Omega^2 / g\) was estimated at 0.2 – 0.4. We note that the value \(s = 0.75\) cm was chosen in order to compare the results of these experiments with the data [1-4].

In experiments, when creating a layer of floating particles, two types of polystyrene particles (density \(\rho_p = 1.04 – 1.06\) g/cm\(^3\)) were used – table 1. BSL spherical particles had a diameter \(d = 0.6\) cm, a volume \(V_p = 0.11\) cm\(^3\), and a mass \(m = 0.12\) g. The second particles are polystyrene granules in the form of an elliptical cylinder with a height of 0.33 cm, major axis of 0.17 cm and minor axis of 0.12 cm; their volume was \(V_p = 0.02\) cm\(^3\); a volume-equivalent diameter of 0.3 cm and a mass of 0.02 g.

The particles had positive buoyancy in relation to an aqueous solution of sodium chloride (density \(\rho_f = 1.11\) g/cm\(^3\) and kinematic viscosity \(\nu_f = 1\) cSt).

| Table 1. Properties of floating particles layer. |
|-----------------------------------------------|
| **Particles** | **N** | **\(h_f\), cm** | **\(c_v\), (%)** |
| **Spheres**    |      |                 |                  |
|                | 1000 | 1.1             | 51.4             |
|                | 2000 | 1.9             | 59.5             |
|                | 3000 | 2.8             | 60.6             |
|                | 4000 | 3.6             | 62.8             |
| **Granules**   |      |                 |                  |
|                | 3000 | 0.9             | 37.3             |
|                | 6000 | 1.4             | 48.0             |
|                | 7500 | 1.6             | 52.5             |
|                | 9000 | 1.9             | 53.1             |
An increase in the number of $N$ particles in the layer ensured an increase in the layer thickness $h_f$. Table 1 for each type of particles shows the values of $N$, $h_f$ and their volumetric content $c_v$. The total depth of the two-layer system was unchanged ($h = 15$ cm), and the thickness $h_f$ of the upper layer of particles ranged from 0.9 to 3.6 cm (figure 1).

The wave pattern was registered with digital cameras DIMAGE Z2 and Canon PowerShot SX50HS (frame rates were 30 and 120 fps) in a moving reference system rigidly connected with the vessel. The resolution of the video images was 0.15 mm/pixel. The subsequent processing of video frames was carried out by the software ImageJ. All experiments were conducted at room temperature 21–22°C.

![Figure 1.](image)

(a) Two-layer system in a rectangular vessel and the initial placement of spherical particles in the upper layer ($h_1 = 2.5$ cm) – hexagonal packing of monodisperse spherical particles. (b) Two-dimensional wave motion of a two-layer disperse system

To estimate the dissipative properties of a two-layer disperse system, we used the logarithmic decrement, defined as $\delta = \ln H_m / H_{m+1}$, where $H_m$ and $H_{m+1}$ are wave heights taken in wave period and estimated from the video materials of wave damping after removal of the excitation – shaking table turned off.

To interpret experimental data, we used the theoretical model [7, 8], in which the asymptotic solution of the nonlinear problem of gravity Faraday surface waves was constructed in Lagrange variables by the Krylov-Bogolyubov method.

3. Results and discussion

In the experiments, regular and breaking waves were observed. If for regular waves the profile is periodic in time and symmetric with respect to the vertical plane drawn through the wave antinodes, then in the case of breaking Faraday waves, individual drops break off the free surface of the liquid – see figure 2a. For water and an aqueous solution of salt as homogeneous liquids, the maximum steepness of the regular waves was $\Gamma_m = H_m / \lambda \sim 0.22$ ($H$ is the wave height; $\lambda = L$ is the wavelength for the second wave mode).

However, placing a layer of floating spheres on top of salty water drastically changes the wave pattern – we observe regularization of breaking waves (figure 2b). The wave shown in the photo has a height of $H$
= 17.1 cm, there are no signs of breaking of the standing gravity wave. The steepness of the wave is $\Gamma_m = H_m / \lambda \sim 0.34$, which significantly exceeds the corresponding value for water ($\Gamma_m \sim 0.22$).

The dispersed system in figure 2b behaves like a two-layer fluid oscillating in the barotropic regime [3, 4]. There are no small-scale perturbations of the free surface, leading to the formation of the collapsing cavity and ejection of the jet from the growing crests (see figure 2a). As shown in [3, 4] the effect of the upper layer of viscous fluid on the process of regularization of breaking standing Faraday gravity waves on the free surface of a two-layer system relates to formation of an emulsion layer which ensures an additional dissipation of wave energy. In the case of floating particles, we have an upper layer of concentrated suspension over a layer of the dispersion phase (salty water); for this system, additional dissipation is determined by the behavior of particles in suspension.
Figure 2. (a) The breaking wave on free surface of salty water – sequence of snapshots of liquid free surface at the stage of transition from the wave trough to wave crest at vessel centre; $\Omega = 21.83$ s$^{-1}$. (b) The regular wave on the free surface of a “two-layer fluid” formed by a layer of floating spheres and an aqueous solution of salt ($\Omega = 20.69$ s$^{-1}$, $H = 17.1$ cm, $h_1 = 3.5$ cm). The time (in seconds) is indicated at the bottom of each frame; video – 120 fps.
Figure 3. Resonance dependences of $H(\Omega)$ in the case of regular waves: 1-2 – water and salty water (homogeneous liquids, $h = 15$ cm); 3-6 – a layer of floating spheres ($h_1 = 1.1, 1.9, 2.8$ and 3.6 cm); 7-10 – a layer of floating granules ($h_1 = 0.9, 1.4, 1.6$ and 1.9 cm); 11 – calculated resonance dependence $H(\Omega)$ according to [7, 8].

In experiments, the resonant dependences of the steady-state wave height $H = H(\Omega)$ on the vessel vertical oscillation frequency $\Omega$ were used as the integral wave characteristics of regular Faraday waves – figure 3.

It can be seen that, in comparison with homogeneous liquids (1, 2), the height $H$ of regular waves increases with increasing thickness $h_1$ of the suspension layer. And this is true for both types of particles - spheres and granules (3 – 10). Between the resonance dependences $H(\Omega)$, there is no frequency shift to the low-frequency region, which is typical for experiments [3, 4] with the upper layer of a viscous liquid in a two-layer system. In the latter, this shift was associated with a decrease in the natural frequency due to an increase in the equivalent viscosity of the system. Note that all the dependencies (1-10) are perfectly described by the theoretical graph (11).

Figure 4. Dependencies of limiting steepness $\Gamma$ of the surface gravity wave on upper layer thickness $h_1$ at the total depth of a two-layer liquid of $h = 15$ cm: 1 – water / salty water; 2 – floating particles (spheres / granules); 3 – seed oil–water (data from [3, 4]); $h^* = h_1 / h$

Figure 4 shows the dependences of the limiting steepness $\Gamma$ of regular waves on the thicknesses $h^*$ of the layer of floating particles (2) and the upper layer of seed oil (3) (experimental data [3, 4]).
In the case of floating particles, the wave steepness increases with increasing thickness \( h_1 \) of the upper layer and reaches a value of 0.38, which is higher than the steepness of the regular wave on the surface of the water \( (\Gamma \sim 0.22) \) or the seed oil-water system \( (\Gamma \sim 0.3) \) – figure 4.

According to results [1–4], the dissipation of wave energy is a determining factor for the regularization of the breaking Faraday waves. Laboratory experiments [6] on the enhanced damping of surface waves by floating spherical particles showed that waves were arrested in finite time. In order to verify conclusions [6], a detailed analysis of the decay process of the second wave mode was carried out. The results of this analysis are discussed below.

Figure 5 shows semi-logarithmic graphs of the amplitude curves of damped waves on the free surface of homogeneous (1) and two-layer (2–4) liquids. It is seen that there is a purely exponential attenuation with decrements \( \delta = 0.06 \) for water and salty water and \( \delta = 0.11, 0.23, 0.31 \) for seed oil–water system. This means that the amplitude curve can be described by a function

\[
y = H / H_0 = \exp(-\delta z)
\]

that solves the equation

\[
\frac{dy}{dz} = -\delta y \quad (z = t / T ; T \text{ is a wave period})
\]

The situation changes in the case of a layer of floating spheres – figure 6. The exponential function \( \exp(-\delta z) \) is not able to describe the entire process of wave attenuation in the presence of a layer of spheres. The discrepancy between the experimental data (2) and the approximating function (3) begins at \( H / H_0 \) of the order of 0.25-0.3. The best approximation (4) of the experimental data (2) in figure 6 is a function of the form

\[
y = H / H_0 = (1 - \frac{z}{\tau_0})^\eta
\]

that coincides with the conclusions of study [6].

It should be noted that with non-exponential attenuation, the differential equation for the dimensionless wave height \( y \) takes the form [5, 6]
\[
\frac{dy}{dz} = -\alpha y^n ,
\]

where \(\alpha = n / \tau_0\), \(m = n - 1\).

The damping of standing surface waves in the presence of a layer of floating spheres and granules is shown in figure 7. It can be seen that the experimental data for all thicknesses \(h_1\) used are well approximated by a power function of the form \(H/H_0 = (1 - z / \tau_0)^n\) whose parameters are given in table 2.

| \(N\) | Spheres | Granules |
|------|---------|----------|
| 1000 | 2000    | 3000     |
| 4000 | 3000    | 6000     |
| 7500 | 9000    |          |
| \(h_1\), cm | 1.1 | 1.9 | 2.8 | 3.6 | 0.9 | 1.4 | 1.6 | 1.9 |
| \(\tau_0\) | 23 | 21 | 15 | 13 | 23 | 18 | 23 | 18 |
| \(n\) | 2.8 | 2.9 | 2.3 | 2.6 | 2.3 | 2.4 | 3.3 | 2.3 |
| \(\delta\) | 0.146 | 0.166 | 0.166 | 0.250 | 0.131 | 0.165 | 0.165 | 0.160 |

In respect that the exponential function \(H/H_0 = \exp(-\delta z)\) approximates well the attenuation data to the level of \(H/H_0 \sim 0.3\), the corresponding decrement values are given in the last row of table 2.

In the experiments, wave attenuation was studied at the initial height \(H_0 < 8\text{–}5\) cm; therefore, non-exponential damping appears at \(H < 2\text{–}1\) cm. On the other hand, the experimental estimates of the decrement \(\delta\) do not exceed 0.25 (see table 2), which is significantly lower than \(\delta \sim 0.3\) when using the upper viscous liquid layer [3, 4].
4. Concluding remarks

We have presented novel experimental results on effects of the upper layer of floating particles on the process of regularization of breaking standing gravity surface waves.

It is shown that the use of the upper layer of spheres or granules significantly changes the dynamics of the wave mode – wave regularization is observed with complete suppression of the breaking mechanisms. Floating particles increase the limiting steepness of standing regular wave to 0.38 without changing the natural wave frequency.

Our experiments confirmed result [6] on the non-exponential damping of standing gravity waves in the presence of a layer of floating particles.

To identify the physical mechanism of regularization of breaking standing gravity waves by a layer of floating particles, the behavior of particles in the layer of oscillating concentrated suspension should be considered. This is the task of our future research.

References

[1] Bazilevskii A V, Kalinichenko V A and Rozhkov A N 2018 Viscous regularization of breaking Faraday waves JETP Letters 107(11) 684–689
[2] Bazilevskii A V, Kalinichenko V A and Rozhkov A N 2018 Effect of fluid viscosity on the Faraday surface waves Fluid Dynamics 53(6) 750-761
[3] Kalinichenko V A 2019 Regularization of barotropic gravity waves in a two-layer fluid Fluid Dynamics 54(6) 761-773
[4] Kalinichenko V A 2019 Effect of an upper layer of viscous liquid on breaking surface gravity waves J. Phys.: Conf. Ser. 1301 012017
[5] Squire V A 2018 A fresh look at how ocean waves and sea ice interact Phil. Trans. R. Soc. A 376 20170342
[6] Sutherland B and Balmforth N J 2019 Damping of surface waves by floating particles Phys. Rev. Fluids 4(1) 014804
[7] Nesterov S V 1969 Parametric excitation of waves on the surface of a heavy fluid Morskie Gidrofiz. Issledovaniya 3(45) 87–97 (in Russian)
[8] Kalinichenko V A, Nesterov S V, Sekerzh-Zen’kovich S Ya and Chaykovskii A A 1995 Experimental study of surface waves with Faraday resonance excitation Fluid Dynamics 30(1) 101–06

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