Formation of vortex structures by noncollinear waves on the water surface

A V Poplevin, S V Filatov
Institute of Solid State Physics, Russian Academy of Sciences, 142432, Chernogolovka, Moscow region, Russia

E-mail: faraldos@issp.ru

Abstract. The generation of a large-scale vortex flow by gravity waves on the water surface has been experimentally studied. It is shown that the mechanism of vortex system attenuation changes with an increase in the relative pump amplitude. The wave amplitudes have been experimentally determined at which the experiment is not described by a theoretical model. The experimental results agree well with the developed theoretical model.

1. Introduction

In nature, a significant part of gas and liquid flows occur in the form of vortex motion, have been studied for quite a long time.

A curious fact is that vortices can be generated as a result of the interaction of surface waves. This phenomenon was observed in the experiments [1,2,3], where the waves were excited in a vessel performing vertical oscillations as a result of the Faraday parametric instability. In [4], the vortex motion was formed by waves generated by wave generators. A theoretical model was also developed in this work, which describes the formation of vortices by perpendicular standing waves, taking into account the effect of a thin film that can be formed on the water surface and can change significantly the experimental results.

According to the developed theoretical model, the vorticity on the surface of a liquid $\Omega$ is described by the expression:

$$\Omega(x, y, 0, t) = \left[\frac{\varepsilon^2}{2\gamma(\varepsilon^2 - \varepsilon\sqrt{2} + 1)} + \sqrt{2}\right] \times Erf\left(\sqrt{2\nu k^2 t}\right) + 1\right] \times \Lambda(x, y),$$

$$\Lambda(x, y) = -H_1 H_2 \omega k^2 \sin(kx) \sin(ky).$$

where $\varepsilon$ is the dimensionless parameter of a film, $Erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x d\xi e^{-\xi^2}$ is the error function, $\gamma = \sqrt{\nu k^2 / \omega}$. This theoretical model is valid for both capillary [5] and gravity waves [4].

2. Experimental methods

The investigations were performed in an experimental setup, the scheme of which is presented in Fig.1. The setup consists of a bath with a length of 70 cm, a width of 70 cm, and a height of a 25 cm,
and a wall thickness of 1 cm which was made from glass. The bath was placed on a Standa vibration isolation table with an air suspension and was filled with distilled water with a total volume of about 50 l to a depth of 10 cm. The bath was covered on top with a plexiglass cover.

Wave generators each consisting of an actuator and a plunger were mounted on a supporting frame; they excite waves on the water surface. In order to excite waves on the water surface, plungers were used which were stainless-steel rods with a diameter of 10 mm and a length of 300 mm. Pioneer TS-W254R subwoofers with a rated power of 250 W were used as the actuators. A sinusoidal signal generated by a dual-channel generator and amplified by a signal amplifier was supplied to the subwoofers.

To visualize the motion of a liquid, a white powder of PA-12 polyamide particles was deposited on the water surface. The Polyamide is in a semi-immersed state, since the particle density is slightly less than the density of water. The particles on the surface were illuminated by the LEDs placed along the bath perimeter. An oscillating the water surface was recorded by a Canon EOS 70D camera at a rate of 24 fps which was located above the bath.

The PIVLab code [6] for MATLAB was used to process resulting video images. It allows calculating the field of displacements between the images by the method of cross-correlation processing of two images. Video Recording processing, as well as the processing algorithm, is presented in [7].

For each experiment, the dimensionless parameter of a film was determined by the method described in [4]. In the presented experiments, its value was in the range of 0.62 - 0.65.

3. Experimental results and discussion

In the experiments, the waves were excited by two plungers, one of which was perpendicular to the wall of the experimental bath, and the second one was rotated by the angle $\alpha = 18^\circ$ (see Figure 1 (b)). The pump frequency was $f = 2.34$ Hz. Figure 2 (a) shows the modes that were excited on the water surface (red dots). The Wave vector difference was $k_1 - k_2 = 0.14$ cm$^{-1}$. The similar difference was observed in the distribution of wave velocity amplitude [8] in the k-space 180 s after switching on pumping (figure 2 (b)).
Figure 2. (a) Resonant modes in the system. The Distance between the modes is $\frac{2\pi}{L} = 0.045 \text{ cm}^{-1}$, where $L$ is the length of a bath. (b) Distribution of velocity amplitude in the $k$-space 180 s after switching on pumping. The wave amplitude is $H_0 = 0.3 \text{ mm}^{-1}$.

The similar vector difference is also seen in the distribution of vorticity amplitude in the $k$-space at the same amplitude of the pump wave (Figure 3 (a)). In the distribution of a vorticity field in the space, depicted in Figure 3 (b), one can see three large-scale vortices, the size of which corresponds to the wave vector in the vorticity amplitude distribution.

Figure 3. (a) Distribution of the Fourier transform of the vorticity amplitude over the wave vectors 180 s after switching on pumping. (b) Distribution of vorticity over the water surface.

Figure 4 (a) shows a graph of the time dependence of vorticity as a function of the relative pump amplitudes. With an increase in the pump level, the vorticity increases. The time dependence of vorticity, normalized by the wave velocity amplitude at different wave amplitudes, is illustrated in Figure 5 (b). At low pump amplitudes, the vorticity increases with time and quantitatively agrees well with the theoretical model. With the Reynolds number $Re = \frac{\Omega}{\nu k^2}$ not exceeding $Re < 50$, the theoretical model describes well the performed experiments. However, with an increase in the amplitude, the measured vorticity is described by a theoretical dependence only in the early stages.
Figure 5 (a) illustrates distribution of the Fourier transform of the vorticity amplitude over the wave vectors 500 s after switching off pumping with a wave amplitude of 0.6 mm. The peaks characterizing the maximum of the vorticity amplitude shifted towards large wave vectors from $0.15 \text{ cm}^{-1}$ to $0.19 \text{ cm}^{-1}$.

(a) $H_0 = 0.6 \text{ mm}$, 500 s after switching off pumping
(b) $H_0 = 1.1 \text{ mm}$, 94 s after switching off pumping
(c) $H_0 = 1.7 \text{ mm}$, 135 s after switching off pumping

Figure 5. Distribution of vorticity amplitude in the k-space after switching off pumping (a, b, c) for pump amplitudes of 0.6 mm, 1.1 mm, and 1.7 mm.

With an increase in the pump amplitude, the character of attenuation changes. Figure 5 (b) shows the vorticity distribution in the k-space 96 s after switching off pumping with a wave amplitude of 1.1 mm. The figure demonstrates redistribution of vorticity from large wave vectors towards the small ones. After this, the entire vorticity passes completely into small wave vectors.

With an increase in the wave amplitude to 1.7 mm, the system attenuates by a different mechanism. The peaks presented in the vorticity distribution in the k-space 135 s after the switching on pumping (Figure 5 (c)) begin to shift towards small wave vectors which correspond to the vortex motion with a characteristic size comparable to the size of a pool.
4. Conclusions

It has been shown that the theoretical model describes well the experimental data when a vortex flow is generated by waves propagating at an acute angle to each other.

The wave amplitudes and the corresponding Reynolds numbers have been determined experimentally, at which the experiment ceases to be well described by the theoretical model. At the Reynolds number Re > 50, the nonlinear effects increase, and the theoretical model describes the obtained experimental data worse.

It has been found that at different pump amplitudes, the mechanism of vortex system attenuation is different: at a small wave amplitude (0.6 mm), the peaks characterizing the vorticity in the k-space shift towards large wave vectors; at a wave amplitude of 1.1 mm, the vorticity is redistributed from large wave vectors towards the small ones. When the amplitude of pumping wave reaches 1.7 mm, the attenuation mechanism is different from the previous ones: - the vorticity peaks in the k-space shift from large wave vectors towards the small ones.

Acknowledgements

The work was supported by the Russian Ministry of Science and Higher Education grant No.075-15-2019-1893.

References

[1] N Francois, H Xiu, H Punzmann, M Shats 2013 Phys.Rev.Lett. 110 19.
[2] N Francois, H Xiu, H Punzmann, S Ramsden, M Shats 2014 Phys. Rev. X. 4 2.
[3] S V Filatov, M Yu Brazhnikov, A A Levchenko 2015 JETP Letters 102 486.
[4] V M Parfenyev, S V Filatov, M Yu Brazhnikov, S S Vergeles, and A A Levchenko, 2019 Phys. Rev. Fluids 4 114701
[5] S V Filatov, V M Parfenyev, S S Vergeles, M Yu Brazhnikov, A A Levchenko, and V V Lebedev, 2016 Phys. Rev. Lett. 116 054501
[6] W Thielicke, E J Stamhuis, 2014 J. Open Research Software 2 (1) 30.
[7] S V Filatov, A A Levchenko, M Yu Brazhnikov, L P Mezhov-Deglin, 2018 Instruments and Experimental Techniques 61 (5) 135.
[8] A V Poplevin et al 2019 J. Phys.: Conf. Ser. 1309 012018