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Visualization of Two-dimensional Vortex Flows in Thin Oscillating Liquid Films

Kiyashko, S. V.* and Nazarovsky, A. V.*

* Institute of Applied Physics, Russian Academy of Science, Nizhny Novgorod, Russia.

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Abstract : A possibility of visualizing flows using random inhomogeneities of film thicknesses of different colors as particles for visualization is shown on an example of a vortex flow structure in an oscillating thin liquid film. Formation of vortex flows in a thin liquid film containing surface-active substances is investigated in experiments. The film is fixed horizontally along the edges of the cell vibrating in the vertical direction. Spatially homogeneous oscillations of the liquid film can excite different types of waves that generate two-dimensional vortex flows due to nonlinearity. We present results of experimental investigation of the structure of vortex flows in a thin film (0.5-10 μm) with rectangular boundaries. It has been revealed that, if the horizontal size of an inhomogeneous region is much smaller than the size of vortices, the inhomogeneities are transported by vortices and their interference pattern can be used for visualization of vortex flows.

Keywords : Visualization, Vortex flows, Liquid film, PIV, Inhomogeneities.

1. Introduction

Flows in liquid films have been investigated quite intensively in the recent years. An interest in this problem is, evidently, caused by the fact that hydrodynamic flows in a film may be regarded to be almost two-dimensional ones because of a small thickness of the film. Such liquid films are ideal laboratory objects for verification of the two-dimensional hydrodynamic theory. Besides, they offer a wide scope for practical applications in many technologies where free liquid films are employed.

In this research we investigate formation of vortex flows in a thin liquid film containing surface-active substances at transverse oscillations. We make nondestructive measurements of the entire two-dimensional flow field simultaneously employing the Particle Imaging Velocimetry (PIV) technique. It implies visualization of a flow field by means of small tracer particles and analysis of the visualized digital images (see, e.g., Okamoto et al., 1995). However, it is difficult to use solid particles for thin liquid films because the size of the particles must be much smaller than the film thickness that is about 1 μm. For examination of a flow field in a thin liquid film we employ a new method in which small inhomogeneities in film thickness that differ in color are used for visualization of particles. Physical properties of thin films containing molecules of surface-active substances (e.g., soap) have been investigated in ample detail (see, e.g., Rusanov and Krotov 1979; Couder et al., 1989). Vortices in thin films have been intensively investigated beginning with the work of Couder (e.g., Couder 1981). Well known are the works on vortex excitation by a shear layer in air (e.g., Rabaud and Couder 1983; Chomaz et al., 1988), vortices behind a cylinder (Karman street) (e.g., Gharib and Derango 1989) or behind a row of cylinders placed normally to a thin film (e.g., Rutgers et al., 1996), and vortices induced in a film by an air jet (e.g., Couder et al., 1989). Early observations of the vortex pairs excited by acoustic oscillations were described by Taylor (1878). Note that a soap film has a rather complex structure and its properties are different for different temporal scales.

Investigation of vortex generation by an oscillating force was initiated relatively recently and was carried out only for the simplest cases, namely, monochromatic external force and square and circular geometries of the boundaries (e.g., Afenchenko et al., 1997, 1998). In those works it was shown that spatially homogeneous oscillations of a horizontal liquid film may excite flexural antisymmetric waves analogous to standing waves on a membrane. This is accompanied by periodic compression and extension of the liquid film, which may give rise to Marangoni waves. The Marangoni waves may excite vortex motion on the film due to its nonlinearity. The Marangoni waves set up a secondary, spatially periodic, steady streaming flow parallel to the boundary supporting the film which, in turn, drives vortices throughout the liquid film by diffusion. It was revealed that the vortices may be both small, scaling with the size of the wavelength of excited waves, and large, scaling with the size of the system. Experiments verified that vortex flows in a film may be either regular or turbulent, when the film thickness is decreased.

In this communication we will report results of experimental investigation of the structure of vortex flows in a thin (0.5-10 μm) film with rectangular boundaries.

2. Experimental setup

Experiments were carried out with liquid layers formed on rectangular frames. A water solution (5% glycerin and 1% liquid soap) provided a sufficiently long-lived film. The lifetime of the film depended on the amplitude of exciting force and was varied from several minutes at small amplitudes to tens of seconds at large amplitudes. The rectangular frame had the larger side of 10 cm. The frame was placed in a closed container consisting of two parts with a transparent upper lid.

The lower part of the container was fixed to the vibrator platform. A liquid film was formed on the frame in the upper part of the container, after which it was screwed onto the lower part. The container reduced evaporation of the liquid and shielded the film from external air currents.

Spatial patterns were visualized through the interference of the light reflected at the upper and lower surfaces of the liquid layer. A torus-shaped fluorescent lamp was a source of white light, and the lens of a video camera (VHS National-7) or a still camera was at the center of the screen. During vibration, the initially thick film acted as a diffuse mirror reflecting light back to the camera lens from the wave crests where the surface was almost flat. The inclined portions of the film made large angles with the lens of the camera. Consequently, the light reflected at these portions did not get into the lens. In this fashion a shadowgraph image of an oscillating film was produced. Owing to evaporation, the film eventually became thin (about several microns) and at this stage of the experiment colored interference patterns appeared by means of which horizontal motions in the film were visualized. Small inhomogeneities in thickness were produced as follows. First, a wetted plate was moved along one of the sides of a rectangular frame to form a film with large-scale inhomogeneities. Then, small-scale inhomogeneities were either formed in a natural manner in the course of vortex formation in the film or were produced by mixing and disturbing the large-scale inhomogeneities by means of an air jet directed at an angle to the surface. Vertical vibrations of the container with the film were produced by a TIRA Vib vibrostand controlled by a wave generator of sinusoidal oscillations. The appearing structures were visualized in the 20-900 Hz frequency range with acceleration of 3-20 g_0 (where g_0 is the acceleration of gravity).

3. Video images and reconstruction

The patterns of oscillations and vortex flows observed in experiment depended on the film thickness and amplitude. However, because of very complicated measurements of liquid films, we simply evaluated the thickness of stable thin films by their periodic change of color. As the liquid slowly evaporated, the color of the film changed recurrently and, eventually, the film ceased to reflect light and became invisible (the so-called ``black film''). The color of the film was controlled during measurements. Further, the film thickness was calculated for the preceding time instants because recurrence of the color of the film indicates a decrease in its thickness by half a wavelength corresponding to this color.

The amplitude of film oscillations was calculated by data of measurements of the angles of tilt of the film by a laser tiltmeter. A helium-neon laser beam made an angle of about 45^0 to the surface of the film and the reflected beam reached the screen. For nearly sinusoidal vibrations of the film, the oscillation amplitude of the laser beam on the screen was proportional to the film oscillation amplitude.

Flexural waves were observed throughout the entire frequency range of measurements. Standing flexural waves similar to membrane modes were visualized in hexagonal and rectangular cells.

Figure 1 demonstrates the onset of vortex flows in a horizontally inhomogeneous liquid film against the background of flexural oscillations (oscillation frequency 91 Hz, film thickness 2.5 μm). The image on the left shows the colored interference fringe on a soap film with and without vibrations. The picture on the right is a video image of the onset of vortex flows in the presence of vibration.

Fig. 1. Onset of vortex flows in a horizontally inhomogeneous liquid film.

Fig. 2. Stationary picture of vortex flows.

At a later stage of the experiment when the film was thinned by evaporation, two-dimensional vortices were observed. Figure 2 shows a stationary picture of vortex flows (oscillation frequency 91 Hz, film thickness 2.5 μm). It is clearly seen that, in the course of time, the large-scale inhomogeneities in the film thickness disintegrate into a number of small-scale inhomogeneities rotating together with the vortices. A typical pattern of vortex structure formation is depicted in Fig.1. Regular vortices, as a rule, rotated around their center that did not change its position in conformity with the standing field structure. As the external signal frequency was increased, the number of standing waves increased too and, consequently, the amount of vortex pairs and, evidently, summary vortex circulation in the film were almost equal to zero (the neighboring vortices rotated in opposite directions).

Color video images were recorded by a video camera from the beginning of the experiment until the film became invisible, i.e., its thickness became smaller than half a wavelength in the visible spectrum (about 0.23 μm). By comparing successive video pictures and choosing small inhomogeneities of the film as particles for visualization it is possible to construct velocity fields of vortex flows. The smaller the size of the visualized particles, the more accurate the measurements are. When a succession of patterns was compared in the case of low particle concentration, the picture of a stationary vortex field was constructed by determining coordinates of individual particles in a large sequence of frames by means of computer programs or by hand by means of a cursor. In the presence of a large number of particles, the vortex field was constructed by a standard computer PIV technique. An experimentally constructed velocity field of one vortex is shown in Fig.3. The length of one vector in the figure corresponded to 2/25 sec at the external field frequency of 93 Hz. The vortex diameter was approximately 1.5 cm (g/g_0=12.5). The vortex core rotated faster and the rotation slowed down at the vortex edges. When the external force amplitude was modulated, all vortices increased or decreased angular velocities of their rotation simultaneously.

Fig. 3. Experimentally constructed velocity field of one vortex.

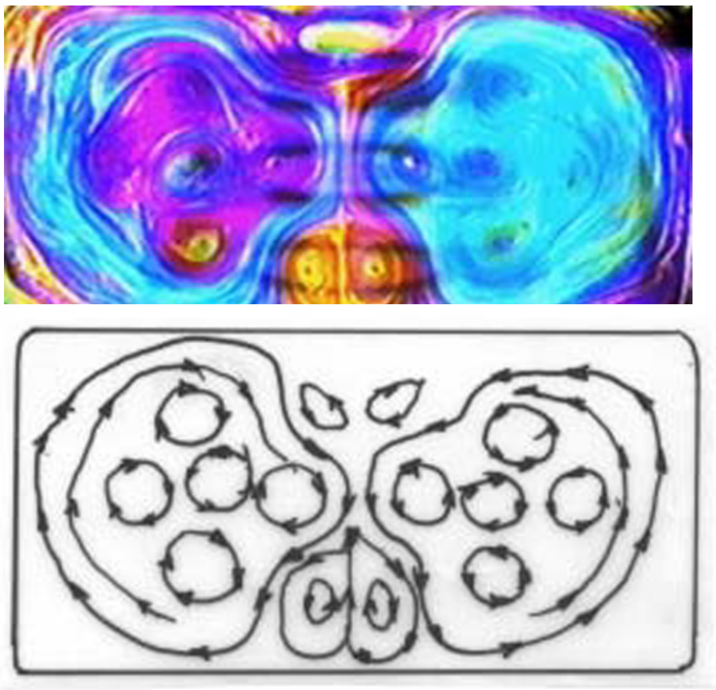

Fig. 4. Flow structure consisting of large-scale vortices against the background of small-scale vortices.

Fig. 5. Two successive images made with an interval of 1 sec.

When the external force frequency was increased, a great amount of vortices were excited in the film not only at its edges but all over its surface, too.

As the film was thinned, larger vortices of different shapes appeared around the small vortices. The flow structure consisting of large-scale vortices against the background of small-scale vortices (film thickness of about 1 μm) is shown in Fig.4. The lower image corresponds to the reconstructed flow structure obtained by the standard PIV technique. Small film inhomogeneities differing by color were used as visualization particles. After that we analyzed their position in successive video images. When an external force was switched off for a short time and then applied again, new stable structures containing secondary vortices of different shapes were formed. The secondary vortices of complex shape are seen distinctly against the background of primary vortices in these figures. As the external force amplitude increased, the secondary vortices became unstable and, hence, the vortex flows became turbulent. Two successive images made with an interval of 1 sec are given in Fig. 5. One can see that the pictures of the flow are quite different.

4. Conclusion

Experimental investigations of vortex flow patterns in thin films have shown that a regular vortex structure with small-scale vortices repeats spatial distribution of the mode excited on a liquid membrane. Small-scale vortices rotate synchronously and all the vortices change their angular velocity simultaneously when external forcing is changed. An increase in external force amplitude leads to collapse of a regular structure and to appearance of vortices of larger scale against the background of small vortices. Depending on initial conditions, stable structures consisting of large vortices of different shapes may appear at fixed parameters of the medium and the external force. We have shown that small inhomogeneities in film thickness can be used as visualization particles for constructing flow fields in thin films.

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Author Profile

Sergey V. Kiyashko: He received his B. Sc. Degree in physics in 1969 from the University of Nizhny Novgorod (Russia) and his Ph.D. in radio physics in 1980 from the Gorky Research Institute of Radio Physics. He worked at the Gorky Research Institute of Radio Physics from 1969 to 1977. Since 1977 he has been with the Institute of Applied Physics of the Russian Academy of Sciences. His research interests cover radio physics, wave interaction in active media, fluid mechanics.

Alexander V. Nazarovsky: He received his M. Sc. Degree in physics in 1998 from the University of Nizhny Novgorod (Russia). He has been with the Institute of Applied Physics of the Russian Academy of Sciences since 1998. His research interests are nonlinear oscillations and waves, theory of dynamic systems and chaos, fluid mechanics, radio physics.