density, velocity, dynamic viscosity, pressure, sound velocity, temperature, and specific-heat ratio of gas; M, Mach number of shock wave; R, gas constant.

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RESONANT EXCITATION OF SPIRAL VORTEX STRUCTURES

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The effect of resonant amplification of the amplitude of spiral vortex structures on the surface of a differentially rotating shallow liquid is detected experimentally.

The importance of nonlinear perturbations in a rotating fluid in heat and mass transport processes has stimulated the study of the dynamics and wave properties of different space-time structures [1, 2]. The problem is often studied experimentally using shallow rotating liquids [3-5]. Spiral surface waves were studied experimentally in [6] using a container with a differentially rotating parabolic bottom. The spiral surface waves were generated in the region of velocity shear and they rotate with an angular velocity not equal to the velocity of rotation of the system as a whole. The possibility of controlling the amplitude of the spiral arms of the surface waves by means of forcing the rotating liquid to flow against a ring of obstacles was predicted theoretically in [7]. The resonant amplification of the amplitude of spiral waves on the surface of a rotating liquid has not been observed experimentally up to now.

The experimental apparatus is a cylindrical container of height 0.25 m with a flat bottom. The sides of the container are made of a material transparent to visible light. The bottom of the container is composed of a disk of radius 0.1 m and two rings of widths 0.1 and 0.3 m. The disk and rings rotate independently of one another with different angular velocities and in different directions [8]. The depth of the liquid (water) used in the experiments was 0.035 m. Motion of the surface of the water was visualized by nonwettable foam plastic particles with diameter of order 500 μm and was recorded by a camera mounted so that it remains at rest. At the shear boundary, i.e., at the distance R_k = 0.1 m, a ring of obstacles was placed. Each obstacle is a hemisphere of diameter 0.04 m and height 0.01 m. The obstacles were mounted on the central disk and the distance between obstacles was constant. The number N of obstacles was varied from one to four. A pressure tensotransducer was used to measure the amplitude of the disturbance [9]. The change of the amplitude of the pressure oscillations at a given radius in the form of an electrical signal was recorded by a digital voltmeter and then fed into a microcomputer for analysis.

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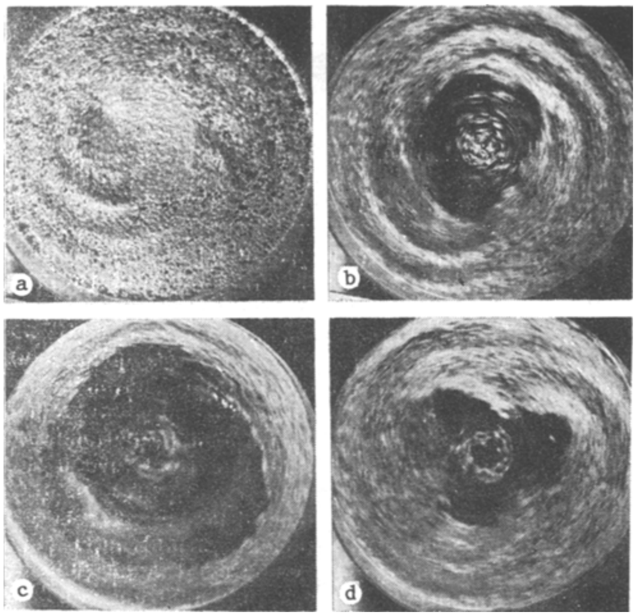

Fig. 1

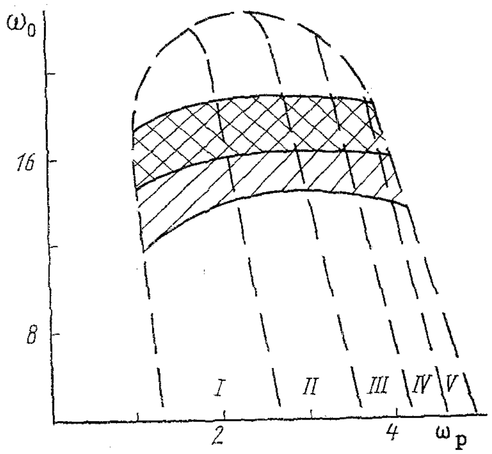

Fig. 2

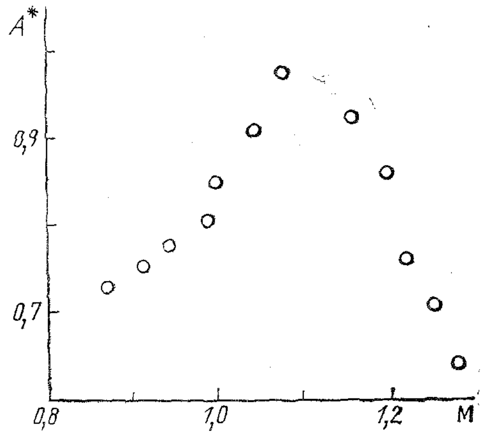

Fig. 3

Fig. 1. Successive stages of development of a system of spiral waves on the surface of a differentially rotating liquid with a ring of three obstacles for different values of the number M: a) M = 0.20; b) 1.00; c) 1.13; d) 1.25.

Fig. 2. Instability curve for a differentially rotating liquid with a ring of obstacles. Dashed lines: boundary of the instability curve: I) region of existence of spiral waves with index m = 2; II) 3; III) 4; IV) 5; V) 6. The singly shaded region is the stable resonance region; the cross-hatched region is the unstable resonance region.

Fig. 3. Dependence of the normalized amplitude of spiral waves A* on the number M for the rotation of a ring of three obstacles in a differentially rotating "shallow" liquid.

Measurements were taken for different values of the ratio of the angular velocity of the disk with the obstacles to the angular velocity of the two peripheral rings. The direction of rotation of the disk and rings was the same. For certain fixed values of the dimensionless number M (the analog of the Mach number) the amplitude of the spiral vortex structures (waves) reached a maximum value. To the right and left of the resonant value of the number M the amplitude of the spiral waves decreased. In order to make this effect more easily visible, buoyant particles were used such that the thin structure of the change in surface density by the spiral waves was not destroyed. The particles did not congregate at the crests in surface elevation and did not disperse in the troughs because of their comparatively large size. Particles are ejected from the center due to the spiral waves. Estimates show that the area free of particles varies in proportion to the wave amplitude. The experiments confirm the existence of resonant excitation in the case of rotation of rings of one, two, three, and four obstacles. The effect of resonance of spiral waves is illustrated in Fig. 1 for the case of three obstacles.

Experiments were carried out in [10] using our apparatus but without the ring of obstacles. A curve was obtained which divides the regime of symmetric rotation from regimes with structure in the form of systems of spiral waves with different symmetry indices. A similar curve can be obtained for the case of rotation with a ring of obstacles.

It was established that the unstable region has a certain width and consists of two subregions corresponding to stable and an unstable resonance (Fig. 2). In unstable the complete removal of gaps, pores, and microscopic discontinuities in the processed surface is not possible. Other methods of quasiperiodic transitions (rocking) are observed for constant external conditions. The average period of rocking is 20 sec. This is the time between amplification and attenuation of the amplitude of the disturbance with the simultaneous increase or decrease of the length of the spiral arms.

The experimental dependence of the normalized wave amplitude on the number M shows a characteristic maximum (Fig. 3). The position of this maximum corresponds to a point on the stability curve lying on the boundary between the stable and unstable resonance regions. The shape of the resonance curve $A^* = f(M)$ corresponds to an expression of the form

$$A^* = [(M_{cr}^2 - M^2)^2 - 4M^2M_\delta^2]^{-1/2}.$$

From the shape of the resonance curve one can estimate the relaxation time $1/\delta$ of the observed structures for the different harmonics. As the number of the mode increases the period of relaxation decreases and for waves with $m = 5$ the period of relaxation becomes equal to the period of rotation of the ring of obstacles.

To obtain wave attenuation the angular velocity of rotation of the liquid would have to be larger than the angular velocity of the obstacles.

Finally, we point out another significant fact. The experiments showed that the shape and size of the obstacles and their number had practically no effect on the variation of the wave amplitude. However, the vertical dimensions of the obstacles must be small in comparison with the depth of the liquid.

The results obtained here represent the experimental confirmation of the theoretical effect of resonant amplification and attenuation of the amplitude of spiral waves generated by a tangential velocity jump in a shallow rotating liquid when it is forced to flow against a ring of obstacles. This effect can be of interest in the practical application of vortex flows in engineering, and also in the forecasting of the evolution of atmospheric vortices with a spiral cloud structure.

NOTATION

h, depth of the layer of liquid; R_k, radius of the shear region; N, number of obstacles in the ring; ω_0, angular velocity of rotation of the central disk; ω_p, angular velocity of the periphery; $\Omega = 1/2(\omega_0 + \omega_p)$, average angular velocity of rotation of the liquid; g, acceleration of gravity; $M = (\omega_0 - \Omega)R_k/\sqrt{gh}$, analog of the dimensionless Mach number; A, amplitude of the spiral waves; A_{max}, maximum wave amplitude; $A^* = A/A_{max}$, normalized amplitude; m, mode number; M_{cr}, value of the Mach number at which resonance is observed; $M\delta = (\delta - \Omega)R_k/\sqrt{gh}$, relaxation value of the Mach number; δ, relaxation frequency.

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