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# Stability of interface between liquids with high viscosity contrast in unevenly rotating cavity

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**Abstract.** The effect of modulation of the cavity rotation rate on the interface of liquids of different densities and high viscosity contrast is studied experimentally. The cavity is a short horizontal cylinder rotating around its axis. The end walls of the cavity form a narrow gap. Under uniform rotation the interface has an axisymmetric shape. With the modulation growth, the axisymmetric boundary loses stability. Instability manifests itself in the appearance of a regular quasistationary relief at the interphase. The relief excitation is associated with the Kelvin-Helmholtz instability. Tangential velocity discontinuity under modulation arises due to various interaction of liquids with the cavity end walls because of viscosity contrast. The viscosity contrast, on the one hand, is responsible for tangential velocity discontinuity; on the other, it has a significant effect on the threshold of Kelvin-Helmholtz instability. It results in decrease of stability threshold and an increase of relief wavelength.

## 1. Introduction

The dynamics of heterogeneous systems in unevenly rotating cavities is an urgent problem due to the widespread use of problems of this type in technology and nature. An example is the modulated rotation (libration) of planets with a liquid core [1], which occurs according to the law  $\Omega = \Omega_{rot}(1 + \varepsilon \cos \Omega_L t)$ . Here  $\Omega_{rot}$  is the rotation rate of the cavity,  $\Omega_L$  is the circular frequency, and  $\varepsilon$  is dimensionless amplitude of librations. In [2], when studying the effect of modulation of the rotation speed of a horizontal cylinder on the sand-liquid interface, it was found that librations lead to the formation of a periodic azimuthal relief on the surface of a granular medium. Sandy hills in the form of dunes are generated by libration-induced oscillating tangential motion of a low-viscosity fluid along the boundary with a granular medium. The latter, due to adhesion to the boundary of the cavity, oscillates together with the cavity, while the low-viscosity liquid rotates at a constant speed  $\Omega_{rot}$ .

The mechanism for generating a relief on the surface of a granular medium [2] has common features with the Kelvin-Helmholtz instability of the interface between two liquids performing oscillating tangential motion [3]. This instability, which manifests itself in the formation of a quasi-stationary (“frozen”) relief at the interface between liquids, was discovered in [4] and, in the limiting case of inviscid



liquids, was described theoretically in [5]. It was shown that in the field of gravity, stability is determined by the critical value of the vibration action, which can be characterized by the vibration parameter

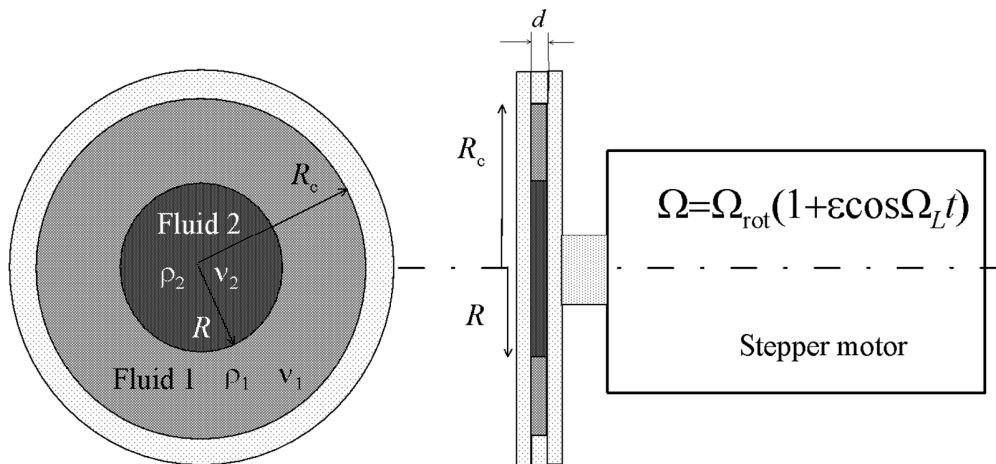
$$B = \frac{\pi\rho}{2(1-\rho^2)} \frac{\Delta U_0^2}{g\lambda_{cap}}.$$

Here  $\rho \equiv \rho_2/\rho_1$  is the relative density of liquids,  $\Delta U_0$  is the amplitude of high-frequency oscillations of the tangential velocity at the interface,  $\lambda_{cap} = 2\pi\sqrt{\sigma/(\rho_1 - \rho_2)g}$  is the capillary wavelength, and  $\sigma$  is the coefficient of interfacial tension. Dimensionless vibration frequencies of liquids  $\omega_1 = \Omega_L \lambda_{cap}^2/\nu_1$  and  $\omega_2 = \Omega_L \lambda_{cap}^2/\nu_2$  are important parameters. The dimensionless viscosity contrast parameter  $K = \nu_2/\nu_1$  characterizes the ratio of dimensionless frequencies, and hence the ratio of Stokes boundary layers at the interface arising in different liquids during their tangential vibrations. The vibration parameter  $B$  is written in such a form, [8], that in the limiting case of high dimensionless frequencies ( $\omega_1 \gg 1, \omega_2 \gg 1$ ) the critical value of the parameter is equal to  $B^* = 1$  when  $k^* \equiv \lambda_{cap}/\lambda = 1$  [5]. It should be noted that further experimental and theoretical studies [6, 7, 8] showed that with an increase in the contrast of viscosities, the threshold for instability of the interfacial boundary significantly reduces. This happens when one of the fluids performs inviscid vibrations, while in the second fluid the viscous boundary layer manifests itself in full.

The purpose of this study is the experimental study of the dynamics of the interface of liquids with a high viscosity contrast in an unevenly rotating thin slotted gap. The presence of closely spaced walls of the cavity determines the qualitative difference of this formulation from the theoretical and experimental studies described above. According to the results of the study, the small transverse size of the channel and the different viscous interaction of liquids with the channel walls play a decisive role in the problem under consideration.

## 2. Experimental setup and technique

The studies were carried out using the setup shown in Figure 1. The cavity is a short horizontal cylinder with a height  $d = 5.0$  mm and a radius  $R_c = 14.0$  cm. Thus, a vertical slotted gap is formed between the end walls of the cylinder.



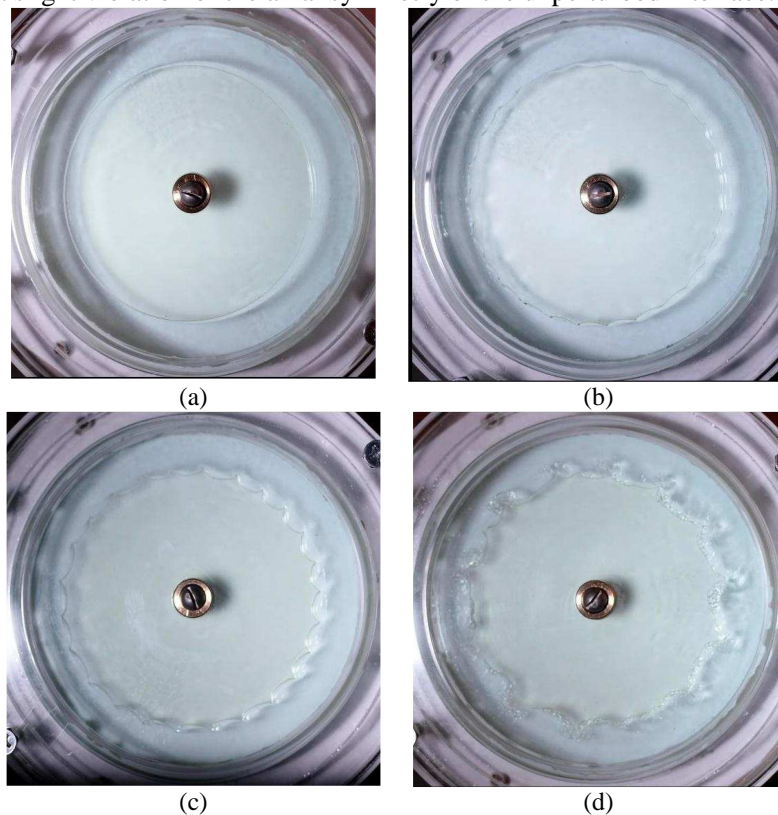
**Figure 1.** Experimental setup scheme: front view and side view

The cylindrical cavity is rotated about its axis according to the law  $\Omega = \Omega_{rot}(1 + \varepsilon \cos \Omega_L t)$  by a stepper motor. The rotation frequency changes in the range  $f_{rot} = \Omega_{rot}/2\pi = 1.5 - 4$  rps, the frequency and amplitude of the speed modulation vary in the intervals  $f_L = \Omega_L/2\pi = 4 - 8$  Hz and  $\varepsilon = 0 - 0.5$ . The cavity is filled with two liquids of different density and viscosity, fluorinert FC-40 (kinematic viscosity  $\nu_1 = 2.2$  cSt, density  $\rho_1 = 1.855$  g/cm<sup>3</sup>) and castor oil ( $\nu_2 = 6.9$  St,  $\rho_2 = 0.960$  g/cm<sup>3</sup>) are used. The interfacial tension coefficient for a given pair of liquids is  $\sigma = 3.0$  mN/m. At uniform rotation, the interphase boundary under the action of centrifugal force has an axisymmetric circular shape. A viscous oil with a lower density is located near the axis of rotation. The radius of the unperturbed interface in experiments is  $R = 5.0$  cm.

### 3. Experimental results

The experiments show that at a given rotation speed, an increase in the amplitude of the speed modulation leads to a threshold excitation of relief in the form of a regular system of hills. During the period, the tops of the hills of a viscous fluid perform small swinging amplitude, except for this. The hills remain motionless in the frame of reference of the rotating cavity.

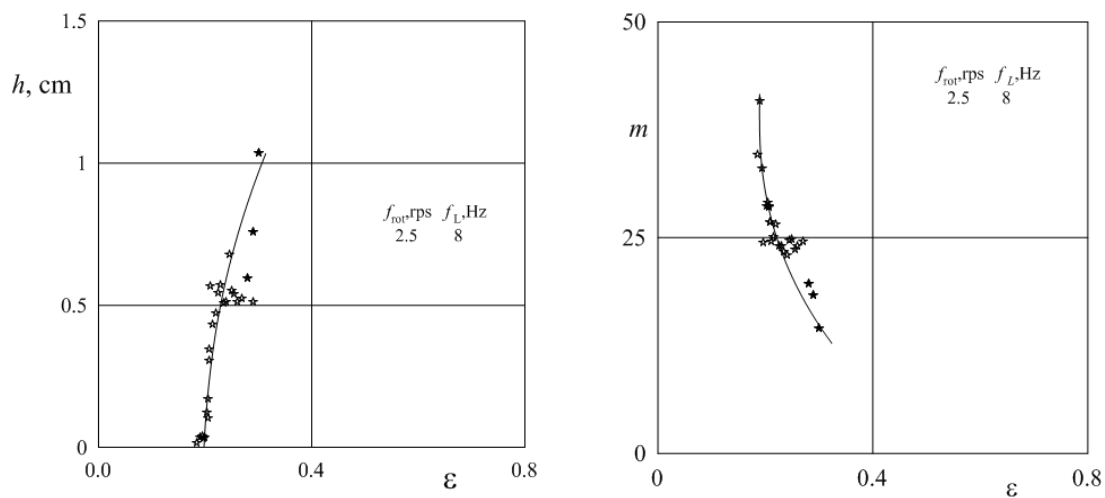
In figure 2 we can see the photographs of the interface up to the buckling threshold (fragment a) and in the supercritical area (fragment b-d). With an increase in the velocity modulation amplitude  $\varepsilon$ , the relief height  $h$  monotonically increases, and the azimuthal wave number  $m$  (total number of hills) decreases (figure 3). It should be noted that the relief of an insignificant height can be observed in a limited area of the interface below the threshold of the critical increase in the relief amplitude. Experiments show that this is connected with a slight violation of the axial symmetry of the unperturbed interface.



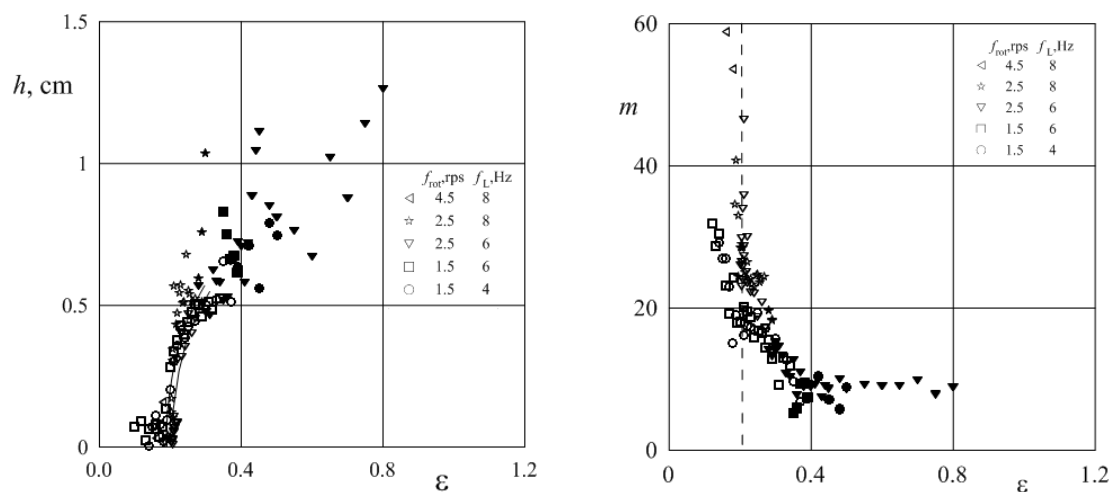
**Figure 2.** Photographs of the interface between liquids at a rotation frequency  $f_{rot} = 2.5$  rps and a modulation frequency  $f_L = 8$  Hz; fragments a-d correspond to  $\varepsilon = 0.165; 0.206; 0.22; 0.30$

The study of the dynamics of the interface, depending on the amplitude and frequency of modulation of the velocity, as well as the frequency of rotation  $f_{rot}$  showed (Figure 4):

- 1) under the conditions of the performed experiment, the frequency of librations has practically no effect on the threshold of the relief appearance (critical value  $\varepsilon$ );
- 2) with a decrease in the rotation speed, the threshold of the relief excitation slightly decreases;
- 3) a decrease in the rotation speed leads to a slight increase in the wavelength;
- 4) at high values of the amplitude of the modulation of the rotation speed, destruction (emulsification) of the interface is observed (indicated by dense signs in the figures), after the appearance of an emulsion at the interface, the relief wavelength practically ceases to change with  $\varepsilon$  (Figure 4).



**Figure 3.** The relief height  $h$  and azimuthal wave-number  $m$  versus the  $\varepsilon$

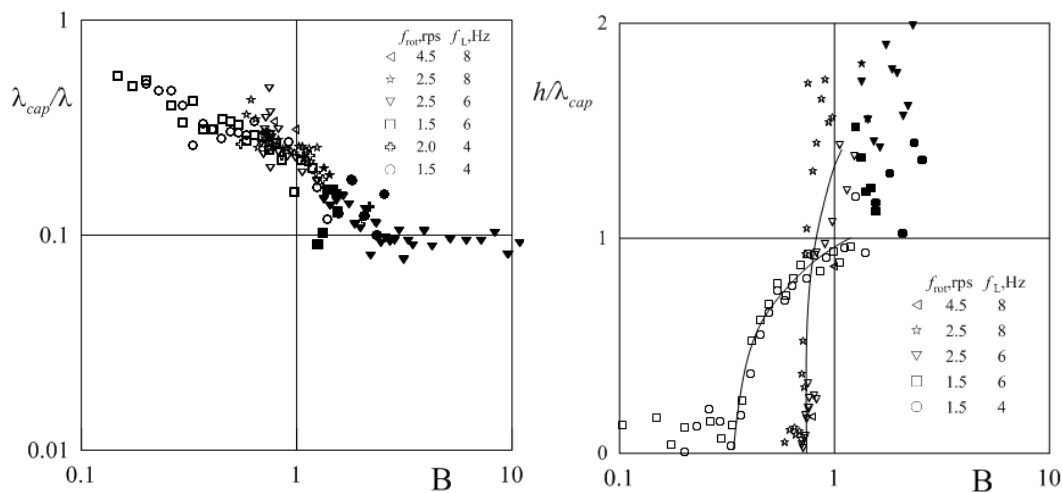


**Figure 4.** Relief height  $h$  and azimuthal wave-number  $m$  versus the  $\varepsilon$  at different rotation rate and the parameters of libration

#### 4. Results and discussion

Let us consider the mechanism of the formation of a "frozen" relief at the interface. As it follows from the estimates, under the conditions of the experiment performed, in the course of oscillations of the cavity with frequency  $\Omega_L$ , the thickness of the Stokes boundary layer that appears near the boundaries of the slot gap in a viscous fluid  $\delta \equiv \sqrt{2\nu_2/\Omega_L}$  varies in the interval  $\delta_2 = 0.5 - 0.75$  cm. Taking into account the fact that the thickness of the gap is  $d = 0.5$  cm, the high-viscosity silicone oil during the rotational vibrations of the cavity oscillates together with the walls, remaining practically motionless relative to the cavity. At the same time, the FC-40 low-viscosity liquid practically does not interact with the layer boundaries ( $\delta_1 \sim 0.03$  cm), which means it rotates at a constant speed  $\Omega_{rot}$ , not responding to the modulation of the cavity rotation speed.

Thus, as a result of different interactions of liquids with the boundaries of the cuvette performing non-uniform rotation, an oscillating azimuthal tangential motion arises at the interface between the liquids, while the amplitude of the tangential jump in velocity is close to  $\Delta U_0 = \Omega_{rot} \varepsilon R$ . Considering the dynamics of the boundary in the frame of reference of the rotating cavity, taking into account the action of the centrifugal force for the vibration parameter, we obtain the expression  $B = \frac{\pi \rho}{2(1-\rho^2)} \frac{R \varepsilon^2}{\lambda_{cap}}$ , where  $\lambda_{cap} = 2\pi \sqrt{\sigma/(\rho_1 - \rho_2) \Omega_{rot}^2 R}$ .



**Figure 5.** Dimensionless wavenumber and height of the "frozen" relief versus the vibration parameter

As we can see in Figure 5, at a relatively high rotation speed, the threshold for the appearance of a relief is close to the theoretical value in the limiting case of low-viscosity liquids [3]. As the rotation speed decreases, the boundary stability threshold decreases. Note that a decrease in  $\Omega_{rot}$  leads to a decrease in  $\lambda_{cap}$  and, as a consequence, to a significant decrease in the dimensionless frequency  $\omega_2$ . The observed decrease in the stability threshold of the interface (the critical value of the parameter  $B$ ) with a decrease of  $\omega_2$  is in qualitative agreement with the experimental and theoretical results [8] in the case of translational tangential oscillations of liquids in a gravity field.

#### 5. Conclusion

It is found that the modulated rotation of a cavity with two immiscible liquids with a high viscosity contrast leads to the loss of stability of the axisymmetric boundary. The excitation of a quasi-stationary

relief at the interface is associated with the development of the Kelvin-Helmholtz instability. The tangential discontinuity of the velocity of liquids arises due to their different viscous interactions with the boundaries of unevenly rotating cavity.

The contrast of viscosities under in a narrow slotted gap is a generator of differential tangential oscillations of liquids near the interface, at the same time it affects the excitation threshold of the Kelvin-Helmholtz instability. The latter is manifested in a decrease of the stability threshold and an increase of the relief wavelength. This is in qualitative agreement with viscosity effect on Kelvin-Helmholtz instability under translational tangential oscillations of liquids.

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