Dynamics of an ensemble of spherical particles under translational vibrations of linear polarisation

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Abstract. This work studies the dynamics of a set of rigid spherical particles in an oscillating viscous liquid under translational vibrations. Experimental data on the influence of vibration parameters and fluid properties on the formation and characteristics of structures are obtained. In the frequency range from 5 Hz to 27 Hz, particles align to form linear structures oriented perpendicular to the direction of the vibrations. For frequencies greater than 27 Hz, the particles are collected on the walls of the cavity. Distance between the linear chains increases with the vibration amplitude according to a close-to-linear law, but decreases inversely as a function of the vibration frequency.

1. Introduction

Studies of vibration effect on multiphase systems are very important for numerous applications, such as extraction and processing of minerals, chemical technology, metallurgy, construction materials industry [1], building [2], and medicine for treatment of some neural and muscular diseases [3]. The use of vibrations has literally revolutionized many industries, providing large technical and economic effects.

Investigations in the field of vibrational hydrodynamics are also of great importance for theoretical reasons. The fundamental questions of the vibration effect on liquids, gases and multiphase media are described in the books and papers by many authors [4-7].

Bodies suspended in a liquid and subject to vibrations can exhibit unusual behavior. According to the Archimedes’ principle, it is well known that a body immersed in a liquid at rest sinks if its density is greater than the density of the liquid, and floats upward in the opposite case. However, under the action of vibrations, the behavior of solids can be changed. Chelomei [8] observed that dense balls immersed in a vertically vibrating cylinder filled with a liquid can rise up and stabilize above a layer of less dense liquid.

The behavior of a body immersed in a liquid contained in a recipient submitted to high-frequency oscillations was analyzed theoretically by [9]. The averaged equations were derived and it was shown that the vibrations change the buoyancy conditions of the solid due to arising of average vibrational force of attraction to the nearest wall. The existence of average attraction force was confirmed experimentally in [10].

The theoretical interaction of two particles in an oscillating liquid was further investigated by [11]. It was shown that an average attractive force appears between particles when the vibrations are perpendicular to the line connecting the particle centers, and an average repulsive force for the vibrations propagating directly along this line.
The interactions of a small number of spherical particles immersed in an oscillating fluid, were studied by Wunenburger et al [12]. They conducted a series of experiments in which small metallic spherical particles were placed in a shallow cavity submitted to horizontal sinusoidal vibrations. The observations have shown that the spherical particles form equidistant chains oriented perpendicular to the direction of propagation of the vibrations.

Voth [13] observed clusters and hexagonal lattices formed by spherical particles in a vertically oscillating cavity filled with a mixture of water and glycerol. Thomas and Gollub [14] studied the fluctuations of these clusters and concluded that the forces arising between the particles are not just the forces of pair interaction. To explain these interactions, various mechanisms have been proposed, including the effect of stationary flow.

The results of experimental and numerical study of the interaction between two metallic spherical particles placed in a liquid-filled container performing horizontal oscillations are presented in [15]. It is found that there is an equilibrium distance between the particles at which a transition occurs from the attractive force at large distances between the surfaces of the spheres, to the repulsive force at small distances.

The interaction of two cylindrical solids with parallel axes in a pulsating flow of viscous fluid directed perpendicular to the plane passing through the axes of the cylinders was investigated in the absence of gravity [16]. It was found that at large distances, the interaction forces tend to bring the solids closer when the viscosity effects are small. With an increase in the relative role of viscosity, i.e. when the distance between the solids becomes smaller or the frequency decreases, the decelerating effect of the friction decreases the velocity drop and reduces the attraction force. At distances less than a certain critical value, the decelerating effect of the viscosity becomes so strong that the interaction force changes of sign: the attraction effect switches into a repulsive effect. This critical distance is of the order of the Stokes length; i.e. it increases with increasing viscosity and/or with the decrease in frequency. An analytical expression for the force acting on the rigid particle in a non-uniform pulsational flow was obtained in [17].

The present paper investigates experimentally the behavior of a system of rigid spherical particles in a container filled with a viscous incompressible fluid and subject to translational harmonic vibrations of high frequency and small amplitude.

2. Experimental settings and investigation method

A multiphase system constituted by rigid particles suspended in a viscous liquid is considered. The container with the liquid is subject to translational vibrations of linear polarization. It is known that under the action of a vibrational force, two spherical particles immersed in an inviscid or low-viscous liquid are attracted if the vibrations are perpendicular to the line connecting the centers of the two particles, and repelled if the vibrations are parallel to the line connecting the particle centers [1]. As the viscosity increases, the sign of the interaction force between the two particles changes to the opposite. In the case of large number of particles, the particles form specific patterns under the action of vibrational forces [2].

Experiments were carried out using an electrodynamic vibrator V650 based on a LDS vibrator. The vibrations were controlled manually using a vibrometer and a generator. Steel balls of the diameter \(d = 4.5 \text{ mm}\) were placed in a rectangular cavity of size \(110 \times 200 \times 15 \text{ mm}\) made of Plexiglas. A digital camera fixed on a tripod above the experimental setup schematically presented in Figure 1, allows tracing the dynamics of the patterns in the cavity.

The vibration frequency in the cavity was set by the generator and the vibration amplitude was varied with an amplifier. The vibration amplitude was changed by steps of 10% of the maximum power of the amplifier, which was 100%. When the required frequency and amplitude of the signal were set, the vibrator was turned on simultaneously to the ventilation unit which is necessary for cooling the vibrator. Under the action of vibrations, the spherical particles randomly located in the cavity at the initial time started to form linear clusters, and after some time when the system reached a stationary
mode, periodicity could be detected between clusters. At this time, the digital camera shot the cavity, and the amplitude of the vibrations was measured with the help of the vibrometer.

Figure 1. Schematic experimental setup. 1 - amplifier UMK-2000, 2 - signal generator of special form GFG-8219A, 3 - electrodynamic vibrator V650, 4 - air handling unit, 5 - digital camera, 6 - portable vibrometer ВВМ-311

3. Experimental results

The present study included two series of experiments. In the first series, the range of vibration parameters during which the periodic structures of particles were formed in the liquid, was investigated. It was found that the formation of structures consisting of linear chains occurs in the frequency range from 5 Hz to 27 Hz. At frequencies greater than 27 Hz, the particles were collected at one of the walls of the cavity. This quasi-equilibrium state of the systems is similar to quasi-equilibrium state of gas-liquid system in a rectangular container subjected to high frequency horizontal vibrations discovered in [18] where this phenomenon was called “orienting effect of vibrations”: interface is oriented perpendicular to the vibration axis. As it was shown in [18] this quasi-equilibrium state corresponds to the minimum of average Lagrangian of the pulsational motion.

Figure 2 shows the experimental photos in a quasi-stationary states of the system formed by steel balls immersed in a water-glycerol solution in the container oscillating with amplitude $A = 0.94$ mm. The system parameters are: number of particles $N = 150$, particle radius $r = 2.25$ mm, liquid density $\rho = 1.2 \times 10^3$ kg/m$^3$, particle density $\rho_0 = 7.8 \times 10^3$ kg/m$^3$, kinematic viscosity of the liquid $\nu = 8.7 \times 10^{-6}$ m$^2$/s, amplitude of container vibrations $A = 0.94$ mm. It is found that during the first rather short stage, the action of vibrations leads to the formation of clusters consisting of several particles. Further evolution of the system consists in the formation of linear chains oriented perpendicular to the direction of vibrations. Why-> develop this point in the discussion

In our opinion, this behavior could be explained on the basis of the analysis of the interaction force between the particles in viscous oscillating fluid at different distances between the particle centers and different mutual orientations of the vibration axis with respect to the line connecting the particle centers (see Introduction Section).
The second series of experiments was carried out with 50% water-glycerol solution at a density of \( \rho = 1.126 \times 10^3 \text{ kg m}^{-3} \) and a kinematic viscosity \( \nu = 3.2 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \), in which 250 steel spherical particles of the radius \( r_0 = 2.25 \text{ mm} \) and density \( \rho_0 = 7.8 \times 10^3 \text{ kg m}^{-3} \) were immersed. Figure 3 shows the dependences of spatial period of the formed quasi-stationary structures (the distance between the chains) \( T \) on the vibration amplitude for two fixed values of the vibration frequency obtained in these experiments. As one can see in Figure 3a, at fixed frequency of vibrations, the spatial period of the structures increases quasi linearly against the vibration amplitude. Comparison of the curves obtained for different frequencies shows that the spatial period of the structures decreases with increasing vibration frequency (see, Figure 3b).

Figure 3a. Spatial period of structures \((T \text{ in mm})\) between structures as a function of vibration amplitude \((A \text{ in mm})\) at frequencies 10 Hz and 20 Hz
4. Conclusions
The dynamics of rigid particles in oscillating viscous liquid have been investigated experimentally. Two series of experiments were carried out. In the first series, the range of vibration parameters was studied, where periodic structures of particles are formed in the liquid. It was found that particles aligned to form linear structures oriented perpendicular to the direction of the vibrations are observed in the frequency range from 5 Hz to 27 Hz. At frequencies greater than 27 Hz, the particles are collected at one of the walls of the cavity.

The second series of experiments were devoted to the investigation of the dependence of the spatial period of the formed structures (the distance between the chains) on the vibration parameters. It is found that the spatial period of the structures increases with the vibration amplitude growth according to a close-to-linear law. Comparison of the curves obtained at different frequencies shows that the spatial period of the structures decreases with the increase in the vibration frequency.

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