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Lift force acting on the cylinder in viscous liquid under vibration

V. Kozlov [a,b,*], A. Ivanova [a], V. Schipitsyn [a], M. Stambouli [b]

[a] Perm State Pedagogical University, Sibirskaia av., 24, 614990 Perm, Russia
[b] Ecole Centrale Paris, Grand Voie de Vignes, 92295, Chatenay Malabry Cedex, France

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ABSTRACT

The averaged lift force acting on a solid in viscous liquid in case of translational or rotary vibrations of a cavity is experimentally investigated. Experiments are performed with a heavy cylinder; different types of vibrations, translational and rotational, are investigated. It is found that the vibrations excite the mean lift force which could provide the suspension of solid even in gravity field. The repulsion lift force acts on the body near the walls of the vibrating cavity. It is caused by the viscous hydrodynamic interaction of oscillating body with the wall and is significant at a distance comparable with the thickness of Stokes layer. The intensification of vibration results in the excitation of tangential lift force, which is caused by the brake of the symmetry of the body's oscillations with respect to the cavity wall. In case of rotary vibrations the lift force of high intensity manifests itself in the bulk of the cavity due to the interaction of body with the oscillating shear flow. The mean dynamics of the solid body in a cavity under the rotary vibrations is determined by the combined action of two averaged vibrational effects—levitation of the body in the oscillating shear flow and hydrodynamic interaction of the body with the wall. In case of translational vibrations the dynamics of the solid is mainly determined by interaction with the walls. The experiments demonstrate that the vibrations have strong mean effect on the bodies in liquid; they could be used for efficient control of solid inclusions in microgravity and must be taken into account in space experiments and technologies.

1. Introduction

Vibrational hydrodynamics—mean behavior of inhomogeneous systems (multiphase, nonisothermal) in oscillating force fields—is an actual scientific domain with great application potential in microgravity conditions. Vibrations and oscillating inertial force fields are specific for space experiments and space flight environment. The mean forces, which are generated due to vibrations, in the absence of gravity could play essential role and should be taken into account. One of the actual problems in the weightlessness conditions is the control of solid inclusions in liquid; the vibrations could be efficiently used for it. The present study is devoted to experimental investigation of mean forces acting on solids in cavity with liquid under vibration; cases of translational and rotational vibrations of cavity are studied. The averaged force is measured using the method of suspension of the body in the gravity field by means of vibrations.

The averaged lift force acts on the solid body which performs the high-frequency oscillations in liquid. It arises as a result of nonuniformity of oscillating velocity field around the body and nonuniformity of the averaged pressure on its surface. In case of a symmetric body (spherical, cylindrical) the mean lift force appears if the solid oscillates near the boundary or another solid. This force was described by Lamb [1] and in case of translational vibrations was studied theoretically by numerous authors in an inviscid limit [2,3]. The lift force becomes notable if the body oscillates closely to another object. At the same time the size of the solid and the distance between the solids (or the solid and the boundary) is to be much larger than the Stokes layer thickness, as this force is of inviscid nature.

The lift force changes significantly if the liquid (independently from the solid) performs high-frequency shear

* Corresponding author.
E-mail address: kozlov@pspu.ru (V. Kozlov).

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Nomenclature

d	diameter of the body, cm
ρ_S	density of the body, g/cm^3
ν	kinematic viscosity of liquid, St
ρ_L	density of the liquid, g/cm^3
f	linear frequency of vibration, Hz
Ω	radian frequency of vibration, s^{-1}
b	linear amplitude, cm
h	distance, cm
ω	dimensionless vibration frequency
δ	thickness of the Stokes layer
W	vibrational parameter
x	coordinate along the axis of vibration, cm
φ	angle of the solid angular orientation, rad
v	averaged velocity, cm/s
ξ	oscillating component, cm
φ_0	amplitude of angular oscillations, rad
R_1	and R_2 are the internal and external radii, cm
H	thickness of the layer, cm
α	mean angle during the period of vibration, deg.
α_0	mean position, deg.
A	amplitude of oscillations, cm
T	period
W_r	rotary vibrational parameter
R_0	mean curvature radius, cm
g	gravity acceleration, cm/s^2
B	dimensionless amplitude of the solid oscillation with respect to the liquid
ρ	relative density of the solid
R	distance from the axis of vibration to the center of the cylinder, cm

oscillations, which are synchronized with the oscillations of the solid in the cavity frame. It takes place under the combined translational and rotary oscillations of a cavity with a liquid and a solid [4,5]. In this case the averaged lift force of vibrational nature manifests itself in the whole cavity volume and is much stronger than in case of translational vibrations. It could be comparable with the gravity force and provides lifting effect and drift of light and heavy bodies in the gravity field.

The theoretical study of the indicated problems assumes that the liquid and the solid perform high-frequency oscillations and the thickness of Stokes layer is infinitesimally small. So, the liquid is considered to be inviscid.

The averaged interaction varies cardinally if the solid oscillates at a distance of viscous interaction with another solid or the cavity boundary which is comparable to the thickness of Stokes boundary layer. The repulsion of the solid from the boundary in this case was found in the experiments with spherical solid in the vibrating cell filled with viscous liquid [6,7]. So, the averaged vibrational lift force acting on the body at the distance of viscous interaction is opposite to the direction of the lift force in nonviscous liquid (attraction of oscillating body to the boundary).

The focus of this paper is to study the dynamics of a heavy cylinder in the viscous liquid in a rectangular cavity subject to horizontal translational vibrations and the dynamics of the cylinder in the horizontal annulus filled with viscous liquid and subject to rotary vibrations about its axis.

2. The dynamics of the cylinder in the cavity with liquid under horizontal translational vibrations

2.1. Formulation of the problem

The Plexiglas rectangular cavity 1 (Fig. 1) $12.00\times5.50\times9.50$ cm^3 is mounted on the plate of mechanical vibrator (detailed description of the vibrator could be found in [8]). The cavity contains the cylindrical body 2, made of a hollow steel tube with the diameter $d=2.00$ cm and length 8.05 cm. The mean density of the body is $\rho_S=1.20$ g/cm^3. The end-walls of the cylinder are sealed and have light-reflecting marks to control the rotary motion of the body.

The cavity is filled with the viscous liquid, gas inclusions are absent. The oils of different viscosity are used: natural oil ($\nu=0.70$ St, $\rho_L=0.92$ g/cm^3), machinery oil I−40 A ($\nu=1.3$ St, $\rho_L=0.88$ g/cm^3), and its mixture ($\nu=0.80$ St, $\rho_L=0.89$ g/cm^3). Viscosity is measured by the capillary viscometer (accuracy is 0.1 St), density—by densimeter (0.001 g/cm^3), frequency of vibrations—by digital tachometer (0.1 Hz), amplitude—by optical cathetometer (0.1 mm).

The plate of the vibrator and the mounted cavity perform translational harmonic oscillations $X=b\cos\Omega t$ along the horizontal axis. The linear frequency $f\equiv\Omega/2\pi$ varies in the range $f=0$–25 Hz, the amplitude—$b=0.1$–5.0 cm.

The liquid viscosity, the frequency and the amplitude of vibrations are varying. During the experiment with definite ν and b the frequency increases (decreases). The observations are performed using the stroboscopic illumination with the frequency of vibration, photo-registration—using the flash. The body motion is studied by high-speed camera of high resolution (Basler A402k).

2.2. Results

In the absence of the vibration the cylinder has a stable position on the bottom of the cell. The increase of

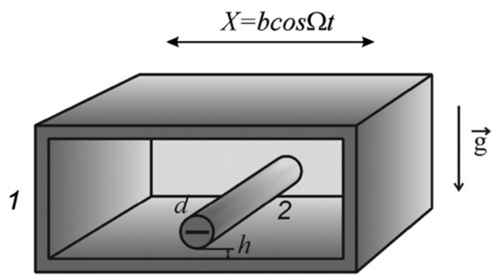

Fig. 1. Sketch of the cavity.