Vibrational suspension of solid block in liquid

Victor G. Kozlov Olga A. Vlasova
victorkozlov2012@mail.ru vlasova_oa@pspu.ru

Abstract

Vibrational dynamics of rectangular solid in filled with liquid rectangular cavity is investigated. The experiments are done with heavy and light solids. Amplitude and frequency of vibration, viscosity and density of fluid, aspect ratio of body, its density and shape of the edges (sharp or smooth edge) vary in experiments.

It is found that longitudinal translational vibrations of cavity provide the suspension of the heavy solid near the cavity bottom (the light one - near the top). In suspension the bodies take the quasi-steady positions at some distance from the walls. After repulsion (in suspension) the oscillations of light body and cavity occur in the same phase. In case of heavy body itвЂ™s oscillations concerning the cavity occur in the opposite phase.

The threshold curves of the light and heavy solid suspension in the fluids of different viscosities are presented on the plane of the governing dimensionless parameters ω, W, here ω is frequency, W - vibrational parameter. The hysteresis in the threshold transitions disappears with increasing the fluid viscosity. The decrease of liquid viscosity brings to change in the character of the threshold transitions: the heavy solid repulses from the cavity bottom abruptly. It is conjectured that the character of solid oscillations changes due to the change of the flow regime.

It is found that the solid (light or heavy) performs the translational inertial oscillations along the cavity boundary and synchronous angular oscillations of small amplitude.

1 Introduction

The average vibrational lift force acting on axisymmetric body in the cavity with an incompressible fluid under translational vibration is subject of many theoretical and experimental works [1]-[9]. Averaged forces are usually calculated in the high-frequency approximation [1]-[3]. The heterogeneity of the pulsation velocity field of fluid around the vibrating body is the source of the average vibrational lift force. Attraction of spherical bodies to the vibrating plate in the liquid was studied in [1]. The problem of solid cylinder vibrational interaction with the cavity wall at a distance comparable to the body diameter was solved in a high-frequency limit in [4, 5].

The repulsive force acting on a spherical body near the boundary under translational vibration of cavity was found experimentally and studied in [6, 7]. This force acts at a distance comparable to the thickness of Stokes layer. The attraction force replaces the repulsive force outside the distance of viscous interaction; the vibrational suspension of heavy body near the top of the cavity was done experimentally in [7]. It is shown that the distance over which the vibrational force changes the sign is determined by the thickness of Stokes layer.

In [8] the dynamics of light cylinder in rectangular cavity with fluid subject to translational vibrations is studied. It is found that the vibrational repulsive force acts on the cylinder oscillating near the boundary the cavity; as a result the light body occupies a stable quasi-stationary position near the cavity top. The repulsive force is associated with the hydrodynamic interaction of the body with the cavity boundary.

The behavior of heavy cylinder in a cavity with liquid at horizontal vibrations is studied in [9]. It is found that dynamics of a heavy body is similar to dynamics of a light body except the phase of oscillation.

The aim of this work is to study the vibrational dynamics of body (both light and heavy) in the form of a long rectangular parallelepiped in the cavity with the liquid. The cavity makes horizontal translational oscillations.

2 Experimental setup and technique

The behavior of solid plate in the cavity of rectangular cross section making high frequency horizontal translational oscillations is investigated. The cavity is filled with a viscous fluid. The body density in experiments varies and takes values smaller and larger than liquid density. The size and the shape of the body also vary. Dynamics of body is studied depending on frequency and amplitude of vibrations in liquids of different viscosity.

The experimental setup consists of the cavity with the body placed in it, which is represented in fig.1, the mechanical vibrator, instrumentation and power supplies. The detailed description of the vibrator can be found in [8]. The cuvette *1* is made of Plexiglas and is a hollow parallelepiped. One of its facets is removable to place the test body *2* inside. Filling the cavity with liquid is carried out through a hole in one end of the cuvette.

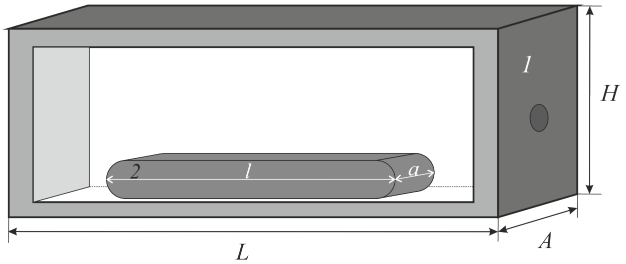

Fig.1

The **light body** is made of polystyrene and has a parallelepiped shape. Body dimensions vary over a wide range: length $l = 6.97 - 8.02$ cm, width $a = 3.04 - 6.50$ cm, thickness $h = 0.64 - 1.61$ cm. The body density varies in the range $\rho_S = 0.06 - 0.6$ g/cm^3. In experiments the shape of the body ends also vary (smooth or sharp edge). The cavity dimensions: length $L = 16.0$ cm, width $A = 6.7$ cm, height $H = 4.0$ cm. The water glycerin solutions of different concentrations were used as a working fluid, kinematic viscosity takes values $\nu = 0.01 - 0.34$ St. This changes the density of the liquid $\rho_L = 1 - 1.20$ g/cm^3. The relative density of the body varied $\rho \equiv \rho_S/\rho_L = 0.05 - 0.55$. Viscosity of the fluid is measured by capillary viscometer (the error is less than 1 percentage), density - by a hydrometer (with an accuracy 0.01 g/cm^3).

The **heavy body** is made of aluminum in the form of a parallelepiped with rounded edges. Body dimensions: length $l = 8.53$ cm, width $a = 2.97$ cm, height $h = 0.91$ cm. Body density is $\rho_S = 2.55$ g/cm^3. The cavity dimensions: length $L = 14.1$ cm, width $A = 3.5$ cm, height $H = 2.05$ cm. As the working fluid the water glycerin solutions are used, kinematic viscosity depends on the concentration and takes values $\nu = 0.05 - 1.29$ St. At fluid density $\rho_L = 1.24$ g/cm^3 the relative density of the body is $\rho \equiv \rho_S/\rho_L = 2.06$.

The mechanical vibrator provides the cavity translational oscillations according the harmonic law $X = b\cos\Omega t$, where b - amplitude and $\Omega = 2\pi f$ - the radian frequency of cavity fluctuations. The vibration frequency varies in experiments $f = 2 - 25$ Hz, the amplitude varies in the range $b = 0.1 - 5.0$ cm. The frequency is controlled by a digital tachometer TD-3M (measurement accuracy 0.1 Hz). To measure the vibration amplitude the horizontal optical cathetometer V-630 is used, the measurement accuracy is 0.1 mm. The length of the track left by the reflective mark located on the front wall of the cavity was used for the cavity displacement measurement.

Technique of the experiment is described below. The cavity with a body is filled with liquid of definite viscosity (without air inside the cavity) and strictly attached to the table of the mechanical vibrator. The horizontal cavity position is checked. The frequency f gradually increases (decreases) at constant amplitude of vibration b. Threshold frequency of separation of one body edge from the top (bottom) of the cavity and the threshold frequency of separation of all the body is defined. After the repulsion the body makes oscillations at some distance from the top (bottom) of the cavity without touching the last.

The threshold return of one side of the body to the upper (lower) boundary of the cavity takes place at decreasing the intensity of vibration. Also the threshold frequency of return of all body when the gap between a body and a ceiling (bottom) cavity disappears is defined.

Experiments are repeated at different values of vibration amplitude, liquid viscosity and the body size. Observation of body behavior, photo and video registration are carried out in continuous and stroboscopic illumination, and also using the flash lamp. In case of high-speed video recording of the cavity with the body in it the powerful light source, such as Peleng 500A is used for illumination. Video filming is carried out by means of video camera of the CamRecord CL600x2 operated from the computer with a speed of 500 frames per second at resolution of 1280 × 1024 points to a shot.

Processing of results of photo and video filming is carried out by means of specialized applied programs on the computer. The displacement of the body to the right with respect to cavity is taken as a positive offset; positive slope of the body is a clockwise.

3 Experiment results

The light body occupies a stable position in the upper part of the cavity (fig.2,*a*), the heavy one - near the bottom (fig.2,*b*) in the absence of vibration under the action of gravity and the buoyancy force.

The light body repulses from the upper boundary of a cavity and holds a steady position at some distance from a wall (the heavy body rises over the lower boundary) under the horizontal vibrations. The lift force is generated by oscillations of the body relative to the cavity under the action of an oscillating inertia force. Repulsion of the body along the entire length from the boundary does not occur simultaneously. With increasing intensity of vibration one of the body edges at first comes off, the whole body is repulsed with a further increase of vibration impact. The gap between the light (heavy) body and cavity top (bottom) increases with further increase in the intensity of the vibrations. The oscillations increase does not affect on behavior of a body. Fig.3,*a* shows the position of light body at a separation of one edge from a cavity ceiling at vibration amplitude $b = 0.97$ cm and frequency $f = 5.9$ Hz, fig.3,*b* - complete separation of the body at frequency $f = 9.0$ Hz. Fig.3,*c* shows complete repulsion of heavy body from the bottom of the cavity ($b = 2.5$ cm, $f = 11.6$ Hz).

Fig.2

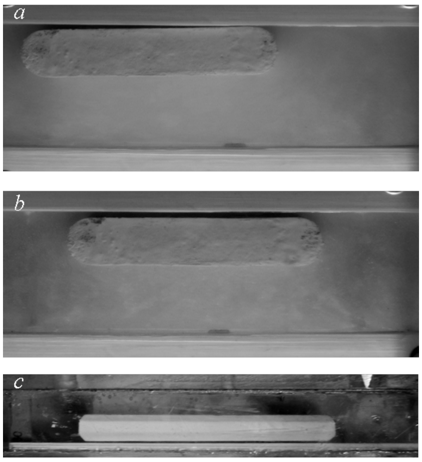

Fig.3

At decrease of vibration intensity the light body comes back to a cavity ceiling (the heavy comes back to a bottom), one of edges falls first.

In experiments with light bodies it is found that regardless of the body size all transitions occur in a threshold manner. The critical value of the vibration frequency decreases with increasing the amplitude.

In experiments with the bodies of different thickness h with a sharp edge (fig.4,a) the hysteresis in the transitions (marked in fig.4 by the shaded area) is observed in the investigated range of amplitudes. With increasing the vibration amplitude the depth of hysteresis increases. In case of smooth edges (rounded edges) with reduced h the hysteresis in the transitions disappears (fig.4,b).

For a body with a sharp edge the threshold curves are displaced with thickness reduction to the area of higher amplitudes and low frequencies of vibrations (fig.4,a); for the body with smooth edge - to the area of smaller amplitudes (fig.4,b).

Hereinafter solid marks correspond to the total repulsion of the body, light marks - the return of one edge to the upper boundary of the cavity. Additionally, the threshold of complete body return to the ceiling is marked on the graph by the dashed line ($h = 0.64$ cm). One can see that the threshold lies just below, that is typical for all experiments.

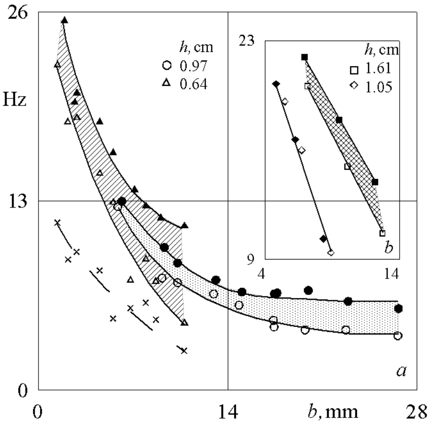

Fig.4

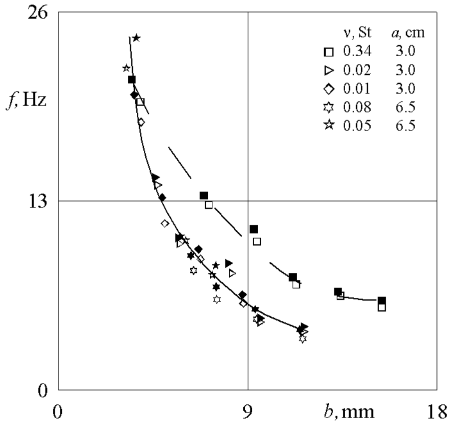

Fig.5

Fig.5 shows the curves of critical transitions of body with rounded edges and a width $a = 3.0$ and 6.5 cm. Width of the body doesn't influence on the threshold values of vibration parameters: the curves are quite close. The threshold transitions for these bodies practically coincide in case of low viscous liquids ($\nu = 0.01 - 0.08$ St). With increasing viscosity ($\nu = 0.34$ St), the curves displace to the higher values of the amplitude of vibration.

The character of oscillations of the body relative to the cavity was studied using high-speed video camera. The results of time-lapse video processing of body motion are presented for two frequencies: at frequency $f = 4.2$ Hz the body is near the cavity ceiling, the gap between the body and the upper boundary is absent; at $f = 14.6$ Hz the body hangs at some distance from the cavity top ($d \neq 0$ cm). The oscillations of the cell and the light body along the horizontal axis are shown in fig.6,*a* - $f = 4.2$ Hz, fig.6,*b* - $f = 14.6$ Hz. The solid marks correspond to the body oscillation concerning the cavity, the light marks - to cavity oscillation in a laboratory reference system.

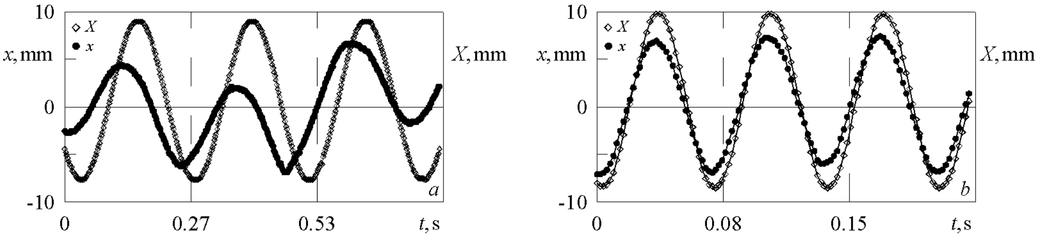

Fig.6

In the case when the gap d is absent, the body vibrations occur with a phase shift compare to the cavity oscillation due to viscous interaction of body with the upper boundary (fig.6,*a*). After the repulsion the body oscillations occur in phase with the cavity, and the amplitude of the body oscillations increases (fig.6,*b*).

At the same time with the translational fluctuations the body makes angular swings of small amplitude. The graph of tilt angle change of light body over time at vibration frequency $f = 14.6$ Hz is presented in fig.7,*a*. Note that the maximum angle of the body is at extreme points of displacement. The width of the gap between the cavity ceiling and the body edges changes as the angle changes its sign. The thickness of a gap of the right edge is presented in fig.7,*b*, in fig.7,*c* - the gap of the left body edge. One can notice that at maximum removal of the right edge from the upper cavity boundary the left edge is in close proximity to the ceiling, but without touching the last.

The behavior of a **heavy body** is similar to behavior of the light body described above. Experiments show that transitions of a heavy body from the cavity bottom also occurs in a threshold manner (fig.8). In experiments with low viscous liquids with increasing the vibration amplitude the hysteresis width decreases (shaded area on the plot). In experiments with viscous fluids ($\nu = 0.42$ St) there is no hysteresis. The solid marks on the plot correspond to the total repulsion of the body from the bottom of the cavity, light marks - the reverse complete body transition to the cavity bottom.

The body motion relative to the cavity is also studied using the high-speed camera. Fig.9 shows the results of time-lapse video processing of the experiment for two frequencies: at $f = 6.0$ Hz (fig.9,*a*) the body is pressed to the cavity bottom ($d = 0$ cm), at $f = 16.6$ Hz (fig.9,*b*, fig.10) the body hangs at a certain distance from the bottom ($d \neq 0$ cm). The graphs of characteristics change with time (fig.9,10) are similar to the same graphs in case of light body (fig.6,7). The difference is that the heavy body is moving in the opposite phase with the cavity oscillations. Also the amplitude of the angular oscillations of a heavy body is about 0.2 degrees, which is several times smaller than the light body (≈ 1 degrees). In this case the left edge of the body (fig.10,*c*) remains practically at the same distance

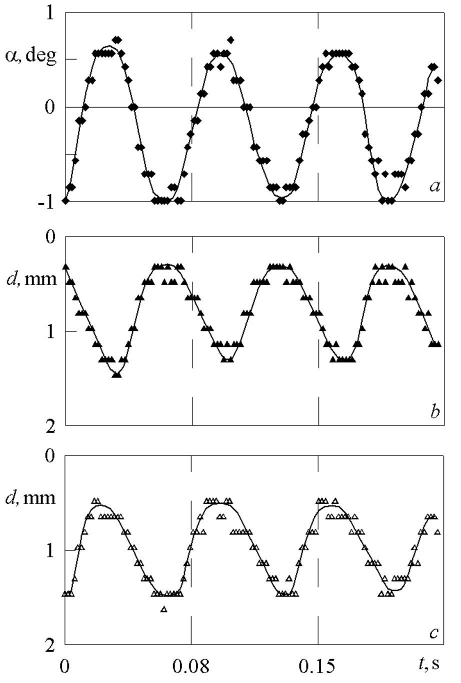

Fig.7

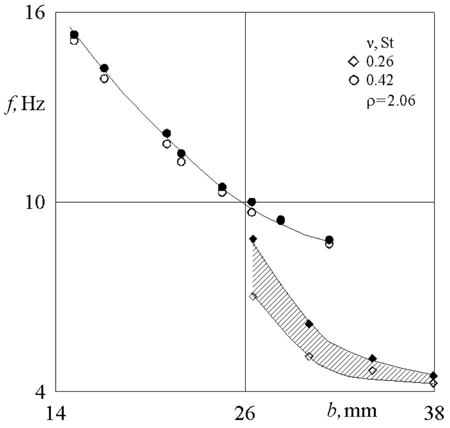

Fig.8

from the cavity bottom during all the oscillation period. The interval of oscillations is marked by the shaded area. The gap width between the right edge and the bottom of the cavity (fig.10,*b*) changes, but the amplitude of oscillation is also significantly less than in case of light body.

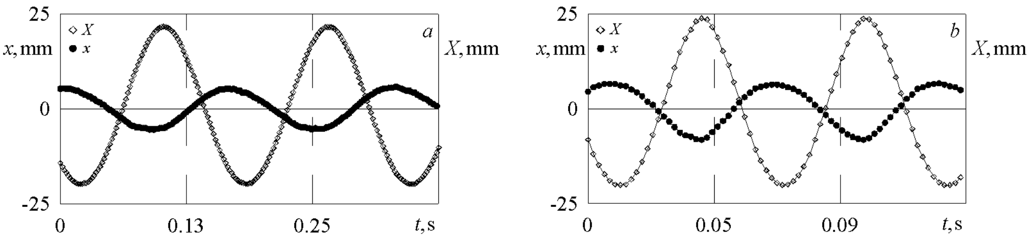

Fig.9

4 Analysis of results

The behavior of the body under vibrations is determined by its interaction with the fluid and the boundaries of the cavity. In works [6]-[9], where vibrational dynamics of spherical and cylindrical bodies in liquid was investigated, the body leaving from the cavity border was defined by viscous interaction, as gap size between an oscillating body and a cavity was comparable with the thickness of Stokes layer $\delta = \sqrt{2\nu/\Omega}$. In experiments with a rectangular body (both light and heavy) the gap size between the body and the cavity border at a complete repulsion doesn't exceed several δ.

Fig.11 shows the trajectory of motion of the right (a) and left (b) ends of the light body relative to the cavity in a dimensionless form under vibration at frequency $f = 14.6$ Hz. The thickness of Stokes layer δ is chosen as a unit of gap thickness between the body and the cavity wall, the amplitude of the cavity oscillations b - for body displacement along the axis of vibration.

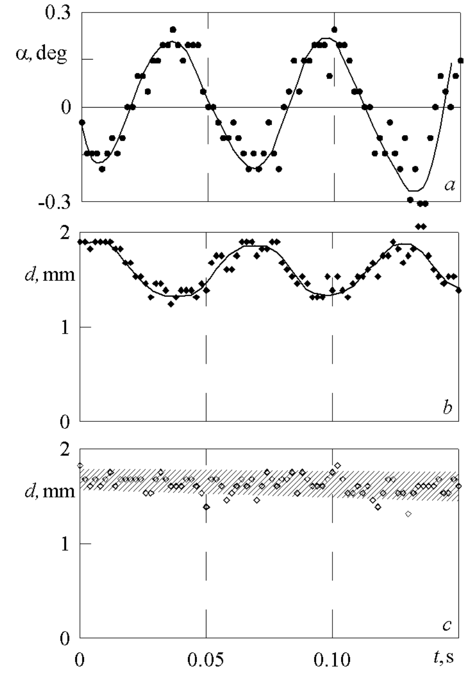

Fig.10

It can be noted that during the period the distance between the edge of the body and the ceiling of the cavity changes. The trajectory of oscillating body motion in the cavity frame looks like a deformed ellipse. The direction of the edge motion along the trajectory is shown by an arrows.

Note that the dimensionless gap d/δ between the end of the body and the cavity top during the period is not constant. The right end of the body (a) is at bigger distance from the upper boundary in extreme right position ($d/\delta \approx 3.5$), than in the extreme left ($d/\delta \approx 1$). To the left edge (b) the character of oscillations is the same; the trajectory is the mirror-symmetric.

Fig.11,c shows the trajectory of the right (black dots) and left (white) heavy body ends relatively cavity at $f = 16.6$ Hz. The dimensionless gap distance does not change much during the period between.

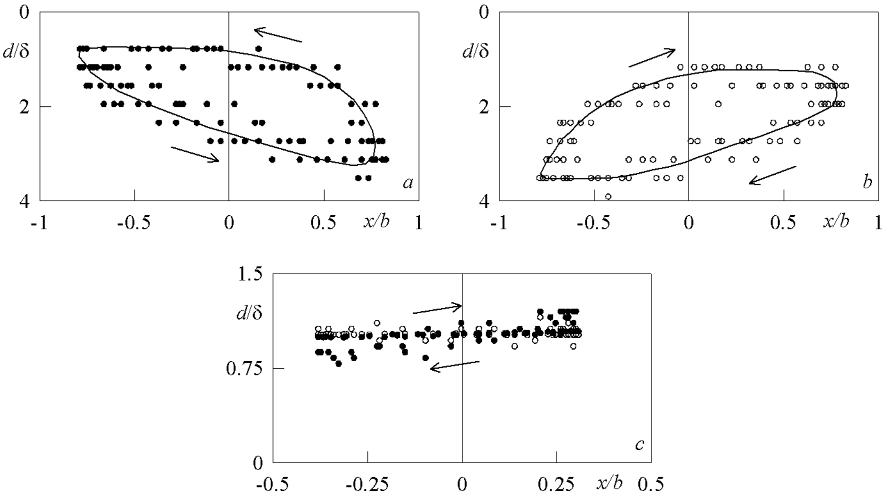

Fig.11

The lift force acting on the cylinder is described in [10].The cylinder streamlined by an oscillating flow of liquid rests on the basin bottom. Equation of the force per unit length of the cylinder looks like: $F_L = \frac{1}{2}\rho_L C_L D B^2 \Omega^2$, there D - cylinder diameter, B - vibration amplitude of fluid in the perpendicular direction to cylinder axis. The value of lift-force coefficient C_L changes from 0 to 1.

In our problem in the case when the body separates from the cavity border completely the lift force counterbalanced the body weight. The force per unit area of the flat body is defined by expression $F_L = \frac{2(\rho-1)}{W}\frac{1}{2}\rho_L b^2\Omega^2$. So lift-force coefficient is associated with the vibrational parameter W and the relative density of the body following ratio $C_L = \frac{2(\rho-1)}{W}$ In the separation threshold from the cavity boundary, lift-force coefficient takes a values consistent with [10] by order of magnitude: for the light body $C_L = 0.88$, for heavy - $C_L = 0.21$. This attests to the generality of the generation mechanisms of lift force acting on the body in the vibrating cavity and in case described in [10], although in our case body, not a liquid, oscillates under the action of oscillating inertial force.

Vibrational lift force experimentally observed and studied in [8] provides swimming of light body close to the cavity top and the heavy body near the bottom. The governing parameters in this problem are dimensionless frequency ω and dimensionless vibrational parameter W (analog of vibrational Froude number).

The curves of threshold transitions on the plane of dimensionless parameters ω, W received in experiments with liquids of different viscosity are presented in fig.12 (a-light, b-heavy body). The solid marks correspond to the threshold value of a complete repulsion of the body, light ones - to its complete return to the cavity bottom. Note that the repulsion of one of the edges of the body precedes the threshold of complete repulsion.

For light body the threshold value W is significantly lower than for the heavy one, while the value of the dimensionless frequency ω is much more. At low dimensionless frequencies for both light and heavy bodies the threshold W sharply increases. As the light body is very receptive to external influences (eg, vortex shedding from the edge of the body), we observe some scattering of points on the graph of threshold transitions (fig.12,a).

The decrease of viscosity of water glycerin solution leads to the rupture of curve of threshold return of heavy body to the cavity bottom (fig.12,b). In experiments with liquid viscosity $\nu = 0.42 - 1.29$ St the body repulsion occurs smoothly. After complete detachment the body behaves stably and sustainably hangs at a certain distance from the cavity bottom. While in experiences with liquids viscosity of $\nu = 0.05 - 0.26$ St the body repulsion occurs instantly on achievement of threshold vibration frequency, the body jump from the lower boundary of the cavity. After repulsion the body randomly moves in a cavity, bending extensively and hitting about cavity end faces. In threshold transitions the hysteresis appears. Presumably the change in body behavior is due to the change of the flow regime, determined by Reynolds number ($Re = h\Omega b/\nu$). So, for less viscous fluids the vortex separation begins at the ends of the body and the body behavior becomes irregular.

5 Conclusion

Vibrational dynamics of rectangular solid in filled with liquid rectangular cavity is experimentally studied. The experiments are done with heavy and light solids. It is found that with increase of vibration intensity the heavy solid repulses from the cavity bottom (the light body repulses from the top) and get the quasi-steady position at some distance from the wall. After repulsion (in suspension) the oscillation of light body and cavity occur in the same phase. In case of heavy body itвЂ™s oscillations concerning the cavity occur in the opposite phase.

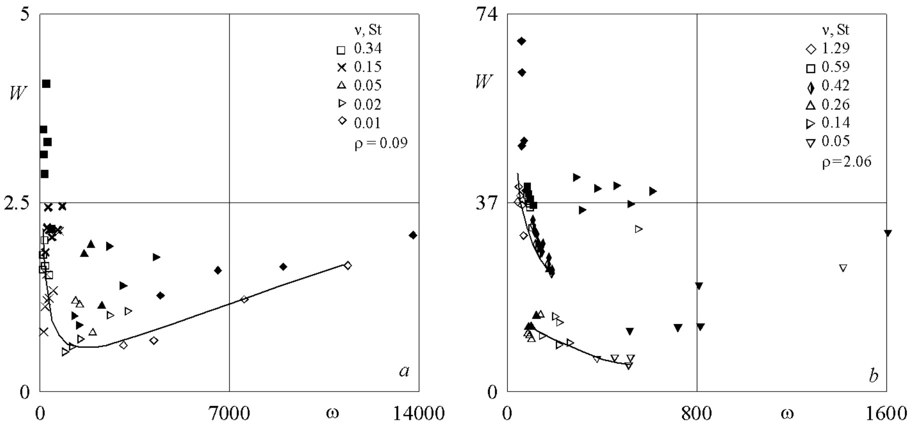

Fig.12

It is shown that the threshold curves of body suspension (for light and heavy solids) in the fluids of different viscosities are in satisfactory agreement in the plane of the governing dimensionless parameters ω, W, here ω is frequency, W - vibrational parameter (vibrational analogue of Froude number). The hysteresis in the threshold transitions disappears with increasing the fluid viscosity.

Acknowledgement

The work is done in the frame of Strategic Development Program of PSHPU (Project 030-*F) with partial support of Ministry of education of Perm region (project C*-26/625*) and grant* 4022.2014.1 *for Leading Scientific School.*

References

[1] Lugovtsov B. A., Sennitskii V. L. On the motion of a body in a vibrating liquid // Dokl. Acad. Nauk SSSR. 1986. 289. No. 2. P. 314-317.

[2] Sennitskii V. L. On the motion of a circular cylinder in vibrating liquid // Prikl. Mekh. Tekh. Fiz. 1985. No. 5. P. 19-23.

[3] Sennitskii V. L. Motion of sphere in vibrating liquid in the presence of the wall // Prikl. Mekh. Tekh. Fiz. 1999. 40. No. 4. P. 125-132.

[4] Lyubimov D.V., Lyubimova T.P., Cherepanov A.A. Motion of a rigid body in vibrating liquid // Convective Flows. PermвЂ™, PermвЂ™ St. Pedagog. Univ. 1987. P. 61- 70.

[5] Sennitskii V. L. Motion of sphere produced by vibrations of another sphere // Prikl. Mekh. Tekh. Fiz. 1986. No. 4. P. 31-36.

[6] Ivanova A.A., Kozlov V.G., Kuzaev A.F. Vibrational lift force acting on a body in a fluid near a solid surface // Dokl. Ross. Akad. Nauk. 2005. 402. No. 4. P. 488- 491.

[7] Ivanova A.A., Kozlov V.G., Kuzaev A.F. Vibrational hydrodynamic interaction between a sphere and the boundaries of a cavity // Fluid Dynamics. 2008. No. 2. P. 31-40.

[8] Ivanova A.A., Kozlov V.G., Schipitsyn V.D. Light cylinder in filled with fluid cavity under horizontal vibrations // Fluid Dynamics. 2010. No. 6. P. 63-73.

[9] Kozlov V., Ivanova A., Schipitsyn V., Stambouli M.. Lift force acting on the cylinder in viscous liquid under vibration // Acta Astronautica. 2012. Vol. 79. P. 44-51.

[10] Sumer B. M., FredsГёe J. (ed.). Hydrodynamics around cylindrical structures. // World Scientific, 1997. No. 12. P. 149-153.

Victor G. Kozlov, Laboratory of a vibrational hydromechanics, Perm State Humanitarian Pedagogical University, Russia
Olga A. Vlasova, Laboratory of a vibrational hydromechanics, Perm State Humanitarian Pedagogical University, Russia