Phenomenon of inversion of the stable states of "gas – fluid – "heavy" particles" system in the vibrating vessels

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Abstract

On the basis of vibrational mechanics approach and method of direct separation of motions the behavior of gas – fluid – solid "heavy" particles system in a vibrating vessel is considered.

The analysis of the received nonlinear equation of slow motions of a particle in the field of standing wave has allowed to come to rather simple conditions of dipping gas bubbles in to the fluid and floating heavier particles. In these instances the system tends to a maximum of potential energy as to a steady state. Peculiar "vibrating instability" of stable without vibration of separate state of gas - fluid and fluid – denser than fluid particles systems in the field of gravity has been revealed. The "slow" self-oscillating phenomena in system have been described. The results are in good agreement with experimental data of the authors and other researchers.

Key words

Vibration, stability, fluid, bubbles, solid particles, self-oscillations

1 . Introduction

Under vibration in the gas medium of the vessel with fluid peculiar nonlinear effects are observed; in particular, suction of gas bubbles deep into the vessel and on the contrary, floating of bodies which are heavier than fluid. In other words, "anomalous" behaviour of the system occurres that is under certain conditions it evolves to the states corresponding not to minimum, but to maximum or close to them value of potential energy.

These and allied questions which are of considerable fundamental and applied importance, were considered in many publications also written by outstanding scientists; the list of references is far from being full. At the same time the problem cannot be still considered exhaustively investigated.

The given work develops and completes the mentioned researches both theoretically and experimentally. Here the conditions of dipping bulbs and floating a "heavy" body have been received in rather simple form by use of vibrational mechanics approach and by the method of direct separation of motions. Results have been compared with experimental data.

In the work only the factors which are minimally necessary for explanation and description of the basic observed effects are taken into account. Thus, the self dynamics of bubble and the corresponding resonant phenomena are only partially considered; nonlinearity of dissipative forces, interaction of particles, cavitation phenomena, vessel deformability have not been considered; a relatively low-frequency vibration has been taken up.

The significant impulse to the researches in this area, including to the given work, was given by the publication of academician V.N. Chelomey [Chelomey, 1983]. The authors devote this work to his memory.

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2. Experimental research

The experiments were carried out on the vibrating stand of "Mekhanobr" institute (Fig. 1).

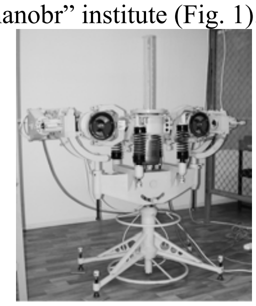

Fig. 1. Photo of installation.

The glass cylindrical vessel – a flask with internal diameter of 60 mm was fixed on the table of the stand; the vessels of smaller and much more major diameters were also used. The vessel was filled with water up to the level of 180 mm, then vertical harmonious oscillations with constant amplitude A = 6.5 mm were imparted to it. The change of system behaviour with slow increase of frequency ω is schematically presented in Fig. 2. The system condition was observed both directly and at stroboscopic lighting with flash rate equal to ω.

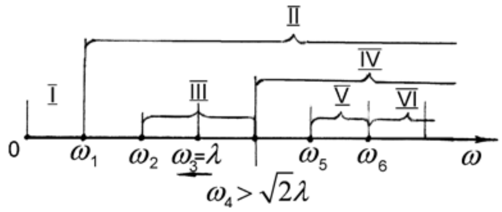

Fig. 2. Critical values and typical variation intervals of vessel oscillation frequency.

In the interval $0 < \omega < \omega_1 = 170\ s^{-1}$ fluid remained clear. Near the surface the gradually growing fluid layer occurred with increase in frequency which was saturated with bubble of various sizes. With $\omega > \omega_1 = 170\ s^{-1}$ there were intensive chaotic oscillations of the fluid surface, and separate splashes amounted to 180 mm. With frequency $\omega = \omega_2 \approx 190\ s^{-1}$ the dipping of bubbles at the total depth of the vessel was observed and at that bubbles with diameter of nearly 1-2 mm were more or less uniformly dispensed in the volume. With $\omega = 200 - 210\ s^{-1}$ the drift of such and smaller bubbles downwards was so intensive that the whole volume of fluid notably grew turbid, solved milk in water. Dipping bubbles were forming an air space ("cushion") near the bottom of the vessel. When the cushion amounted to the certain volume ($\omega = \omega_4 \approx 220\ s^{-1}$) an air bubble swarm, forming "cushion", with characteristic noise uprushed and rose on the surface. After that at the same frequency situation repeated: bubbles were dipped, again forming a cushion etc. In other words the asynchronous excited self-oscillations occurred. Their period was 2÷3 s. At that the general rate of fluid-gas mixture in the vessel was raising to 290 mm which corresponded to gas content $\alpha \approx$38%. In the interval of frequencies $220 \div 230\ s^{-1}$ ($\omega_5 < \omega < \omega_6$) there was the floating of particles, which were denser than water (rubber pieces of 5 mm size and balls of 10 mm size). With frequency $\omega = \omega_3 = \lambda$, close to ω_2, the passage through a resonance corresponding to the frequency of free oscillations of water column on the air cushion took place. At that Sommerfeld's effect was observed [Blekhman, 2000; Blekhman, 2006]. The other experiments are considered below.

3. The equation of particle motion

The equation of particle motion in vibrating fluid or in gas-fluid medium located in the vibrating vessel (Fig. 3), we write down in the form

$$(\rho + \tfrac{1}{2}\rho_0)v\ddot{x} = -k\dot{x} + (\rho - \rho_0)v(\ddot{\xi} + g) \qquad (1)$$

Here x – coordinate of a particle relative to a vessel, counted from undisturbed fluid surface vertically downwards, v– volume of a particle, ρ– its density, ρ_0– medium density, g – gravity acceleration, $k\dot{x}$ – medium resistance force, assumed either linear or linearized. The value of $\frac{1}{2}\rho_0 v$ in the left part of the equation approximately considers the additional medium mass. Absolute medium acceleration in the place of particle location is denoted by $\ddot{\xi}(x, \omega t)$ (we consider, that medium is deformable and $\ddot{\xi}$ changes along x relatively slowly).

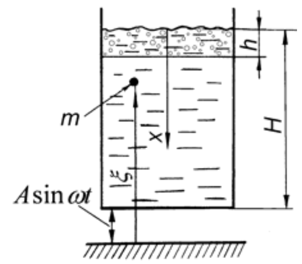

Fig. 3. System scheme.

We'll be finding acceleration $\ddot{\xi}$ from the supposition, that medium is saturated with gas with volume concentration α at some depth $h \le H$ (*H* – an initial level of fluid in the vessel) and can be considered as an elastic rod. As is known, sound speed in such rod for air bubbles with radius $a > 10^{-3}$cm to an accuracy of less than 5 % can be determined by the formula [Batchelor, 1968]

$$c \approx 10/\sqrt{\alpha(1-\alpha)} \quad \text{(m/s)} \qquad (2)$$

This speed is paradoxically low. So, at $\alpha = 0.4$ we have $c \approx 20$ m/s, i.e. more than next lower order than sound speed in the air. This circumstance plays the important role at explanation of the phenomena involved.

From the solution of the wave equation $\ddot{\xi} = c^2\xi'' + g$ under boundary conditions

$$\xi'\Big|_{x=0} = 0\,;\ \xi\Big|_{x=h} = A\sin\omega t$$

(*A* – amplitude of the vessel vibration, we consider, that at $h \le x \le H$ fluid oscillates as a solid body together with the vessel), we find:

$$\begin{aligned} &\ddot{\xi} = -\Psi(x)\sin\omega t, \\ &\Psi(x) = A\omega^2\cos(\omega x/c)/\cos(\omega h/c) \end{aligned} \qquad (3)$$

Allowing for these expressions the equation (1) takes the form

$$\ddot{x} = -k_1\dot{x} + \kappa\left[-\Psi(x)\sin\omega t + g\right], \qquad (4)$$

$$\begin{aligned} &k_1 = k/(\rho + \tfrac{1}{2}\rho_0)v, \\ &\kappa = (\rho - \rho_0)/(\rho + \tfrac{1}{2}\rho_0) \end{aligned} \qquad (5)$$

4. The equation of slow motion (the basic equation of vibrational mechanics). Some motion regularities

The general analytical solution of the nonlinear nonautonomous equation (4) is hardly possible. However this equation differs only in notations from the equation of particle motion in the field of standing wave, considered in particular in the book where for this purpose the approach of vibrational mechanics and the method of direct of separation motion are used. According to this method the solution takes the form

$$x(t) = X(t) + \psi(t, \omega t), \qquad (6)$$

where X – "slow", and ψ – fast component 2π – periodical over ωt constituent with a zero average over ωt. Here for the main slow constituent the equation is written as

$$\ddot{X} = -k_1 \dot{X} + \kappa g + V(X) \qquad (7)$$

where

$$V(X) = -\frac{1}{2}\frac{\kappa^2}{\omega^2 + k_1^2}\Psi'(X)\Psi(X) = -\frac{1}{4}\frac{\kappa^2}{\omega^2 + k_1^2}[\Psi^2(X)]' =$$

$$= \frac{1}{4}\frac{\kappa^2}{\cos^2(\omega h/c)} \cdot \frac{\omega^2}{\omega^2 + k_1^2} \cdot \frac{A\omega}{c} A\omega^2 \sin 2\frac{X\omega}{c},$$

$$(X \le h) \qquad (8)$$

– so-called vibrational force (in this case “vibrational acceleration” but we conventionally use the term "force"). Occurrence of the vibrational force (8) in the equation (7) accounts for almost all effects described in item 2.

The difference between expression (8) and the expression received in the book [Blekhman, 2000] lies in the using expression (3) and also in the fact that in the solution of fast motion equation it is used not so-called purely inertial approximation, but the viscous resistance force $k_1\dot{\psi}$ is also considered; it can turn out to be essential in case of fine particles at rather low frequencies ω (see below). Equation (7) after simple transformations is reduced to the equation of pendulum motion, well studied in the theory of nonlinear oscillations. It is noteworthy, that it corresponds to potential system (in the presence of dissipation) whereas the initial equation (4) answers essentially non-conservative system; such systems refer to the class of potential on average systems [Blekhman, 2000]. Consider next equation (7) separately for the case with gas bubbles and solid particles. Here we note some general consequences:

1) If $V(X) << \kappa g$, that is vibrational force is much less than weight of a particle in fluid, then a particle in the steady mode moves with an almost constant speed $\dot{X} = \kappa g / k_1$ (floats in case of a bubble and dips in case of a particle, heavier, than medium).

2) In another extreme case $V(X) >> \kappa g$ the particle "is attracted" as to the stable positions to nodes of wave X_0, where X_0 – the roots of equation $\Psi(X_0) = 0$ (in our case – to the points where $\omega X / h = \pi(0.5 + n), \quad n = 0,1,2,\ldots$), i.e. it moves in the line of decrease function $|\Psi(X)|$ (in our case – in the line of decrease $|\cos\omega X / h|$).

3) In intermediate cases a particle is attracted to points X_*, where $V(X_*) = \kappa g$ and at that $V'(X_*) < 0$; at $\kappa g << V(X_*)$ these points are situated near the nodes mentioned in item 2), their coordinates can be found from the equation given above.

It should be stressed that expression (8) was resulted here at “minimally necessary” suppositions and by means of relatively simple method. Similar expressions resulted at different, more complicated admissions and by means of rather difficult methods are known [King, 1934; Zarembo and Krasilnikov, 1966; Ganiev and Ukrainsky, 1975]. It’s notably that the majority of such expressions contain multiplier $\sin(2X\omega/c)$, however essentially varied in coefficient. It leads to various conclusions about “attraction” of particles to wave nodes or antinodes. Experimental data are also conflicting in a number of cases. Rather exotic dependence of points of attraction on relative density of particles and medium are practically important (if they are true).

Vibration force (8) can be interpreted as radiation pressure determined with the fast constituent of particle motion ψ.

If medium density ρ_0 changes along coordinate X then function $\kappa(x)\Psi(x)$ plays the role of $\Psi(x)$, at that $\Psi(x)$ must be determined from the wave equitation with variable coefficients. Studying such cases is an independent problem. Here we in the main consider step change ρ_0 along x.

5. A condition of gas bubble dipping. The phenomenon of vibrational unstability of an equilibrium position of gas-fluid system in the field of gravity

In the case of an air bubble $\rho \ll \rho_0$ and, according to (5), $\kappa \approx -2$. Then, as it follows from equation (7) if at the boundary of the front of gas phase propagation $X = h$ the inequality $V(h) > 2g$ or, allowing for (8), the relation

$$Q = \frac{\omega^2}{\omega^2 + k_1^2} \cdot \frac{A\omega}{c} \cdot \frac{A\omega^2}{g} tg\frac{h\omega}{c} > 1, \qquad (9)$$

are satisfied, then bubbles will propagate deep in to the vessel formed in a layer with thickness h. If acceleration $\ddot{X}$ is small than bubbles velocity on the front is $\dot{X}\big|_{X=h} = \frac{1}{k_1}\left[V(h) - 2g\right] = \frac{2g}{k_1}(Q-1)$.

Inequality (9) is possible to consider as a condition of vibrational unstability of separate state of gas-fluid system in the field of gravity. It is easy to see, that at not very high frequencies ω, as in our experiments, it can be satisfied only with availability of a gas-saturated layer near to a fluid surface, when sound speed c is comparatively low (as it was mentioned, at $\alpha = 0{,}4$ we have $c \approx 20$ m/s that in the air $c \approx$ 330 m/s, and in water $c \approx 1500$ m/s!). Thus, for explanation of the discussed unstability and bubbles dipping an important point is turbulization of some fluid layer near the free surface with intensive fluid kicks above the surface and with formation of bubbles of different sizes penetrating at significant depth (in conditions of our experiments - up to 5 – 7 sm). Various points of view about physical reason of this effect are expressed (see , for example, [Grigoryan, Yakimov and Apshtein, 1967; Tatevosyan, 1997]. Here we take this effect as experimental fact; we remind that in our experiments it occurred starting with the frequency $\omega = 170\ s^{-1}$ at amplitude of 6.5 mm and remained at the further increase ω that is coordinated with the results of work [Tatevosyan, 1997]. It can be said, that the surface layer is considered by us as the vibrating generator of the bubbles. According to work [Abiev, 2000], the radius of generated bubbles is stable enough and is about 0.7 mm that also corresponds to our observations. Such bubbles at frequencies $\omega < 200\ s^{-1}$ can be considered as solid particles.

Note, that if "capacity" of generator is less, than the bubbles discharge through the section of front $\dot{X}\big|_{X=h}\ \alpha \cdot S$ (S – cross section area of the vessel) then it is natural to expect, that bubbles will dip not as a continuous flow, but in the form of a swarm; it also corresponds to experimental observations.

It should be stressed that according to (9) bubbles dip only if the value of thickness ratio of gas-saturated compressible layer $h\omega / c$ exceeds certain critical value which depends on other nondimensional parameters.

In Fig. 4 there is an areas of changing parameters $A\omega^2 / g$ and $A\omega / c$, specified with condition (9) (shaded area). An upper curve corresponds to a relation $h = 5A$, and a lower one corresponds to $h = 10A$. It is also accepted that $\alpha = 0,4$ and $k_1^2 \ll \omega^2$; the last corresponds at frequency $\omega \approx 200\ s^{-1}$ to bubbles with radius $a > 0,4$ mm and $k = 6\pi\mu a$ (Stokes formula; μ – dynamic viscosity factor). The sign $*$ marks the point corresponding to the beginning of dipping bubbles in our experiments. Evidently, at $h = 10A$ the agreement is rather good.

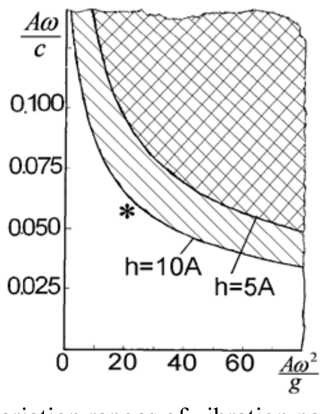

Fig. 4. Variation ranges of vibration parameters when bubbles dip deep into a vessel.

The significance of the layer saturated with bubbles for the initiation of dipping bubbles deep into the vessel is proved by the following experiment. At frequency $\omega \approx 130\ s^{-1}$ when bubbles in a surface layer are still not generated, the air is blown in through the lance in the upper layer or the air balloon in thin rubber covering was placed in it. Both variants at once initiated dipping bubbles deep into the vessel. Similar by implication experiments were carried out earlier in work [Grigoryan, Yakimov and Apshtein, 1967].

Moreover we carried out the experiment with the vessel where fluid surface was closed with polyethylene film. In that case in the whole range of changing frequency ω fluid moved as a single whole together with the vessel; bubbles formation wasn't observed in it. That experiment also proves an important role of fluid compressibility and absence of cavity bubbles formation in the conditions of experiment.

6. The bubbles, drifting to standing wave antinodes

The present consideration covers the case when the particle can be taken as solid-state. This condition at frequencies $\omega < 200\ s^{-1}$ is satisfied by air bubbles with radius less than 1 mm. Such bubbles are "attracted" to the amplitude $|\Psi(X)|$ nodes of a standing wave as to the stable positions. As follows, in particular, from works [Kremer, 1994; Blekhman, 2006], bigger bubbles which frequencies of free oscillations are close or less ω, in the certain ranges of changing ω are gravitated to the points close to the amplitude $|\Psi(X)|$ antinodes.

7. Conditions of floating particles, denser, than fluid

Consider two models of system behaviour leading to the floating "heavy" particles in the vibrating vessel with fluid. In both these models the main role is given to formation of standing wave node inside of fluid column which attracts a particle. *As the first model* it is supposed, that *the column of fluid is uniformly saturated with air bubbles*. Medium oscillations in this case are described by formula (3) at $h = H$. From equation (7) it follows, that a condition of floating the body laying at the bottom of the vessel *(X=H)* is inequality $\kappa g + V(H) < 0$, or, allowing for (8), relation

$$\frac{1}{2}\frac{\omega^2 \kappa}{\omega^2 + k_1^2} \cdot \frac{A\omega}{c} \cdot \frac{A\omega^2}{g} tg\frac{H\omega}{c} < -1 \qquad (10)$$

At gradual increase of frequency ω this inequality will be satisfied, if conditions are satisfied

$$\frac{\pi}{2} < \frac{H\omega}{c} < \pi\ ,$$

$$D = \frac{1}{2} \cdot \frac{\omega^2 \kappa}{\omega^2 + k_1^2} \cdot \frac{A\omega}{c} \cdot \frac{A\omega^2}{g} \left| tg\frac{H\omega}{c} \right| > 1 \qquad (11)$$

The first of these conditions means, that the wave amplitude $|\Psi(X)|$ node is above the bottom of the vessel, and antinode is as though below the bottom.

As the second model consider the system representing *fluid mass* $m_1 = \rho_0 S H$ *, connected with a vessel by a spring of stiffness* c_1 (Fig. 5).

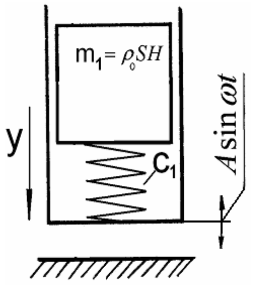

Fig. 5. System scheme with air cushion.

Unlike the first model medium deformability is supposed here not uniformly distributed, but concentrated in the bottom part of the vessel. Such situation emerges naturally. As bubbles are collecting near the bottom of the vessel, air cushion is being formed. Free oscillations frequency of the fluid column on this cushion λ, verging towards value ω_2, decreases (in Fig.2 it is conditionally shown with an arrow ⟵). As a result even if frequency of oscillations ω is kept close to ω_2 and especially at increasing ω, the resonance occurs (it is fixed in the experiment; see point 2).

Amplitude of fluid column oscillations under oscillations of the lower end of a spring according to the law $A\sin\omega t$ (without taking into account dissipation) is

$$G = A/\left|z^2-1\right| \tag{12}$$

where $z=\omega/\lambda$, and $\lambda=\sqrt{c_1/m_1}$ – frequency of free oscillations for which the formula is known ([Nigmatulin, 1987, v. 2, p. 105])

$$\lambda=\sqrt{\varsigma p_0/\rho_0 Y_0 H} \tag{13}$$

Here p_0 – atmospheric pressure, ς – polytropic coefficient, Y_0 – height of purely air space. The following expression is obtained from here for the height of a water-air layer Y_1:

$$Y_1=\frac{Y_0}{\alpha}=z^2\frac{\varsigma p_0}{\alpha\rho_0 H}\frac{1}{\omega^2} \tag{14}$$

When $z=\sqrt{2}$ formula (12) gives $G=A$ and when $z>\sqrt{2}$ we have $G<A$. Simple research shows that these conclusions are true if we take into consideration dissipation at that when $z>\sqrt{2}$ formula (12) is rather exact in the wide range of changing dissipation coefficient. As a result of decreasing amplitude G in comparison with A when $z>\sqrt{2}$, the condition of bubbles dipping (9) stops being fulfilled and fluid according to the experiment becomes clear; it oscillates like a solid body on the "soft" spring.

Estimate vibrational force $V(Y)$ when $z>\sqrt{2}$. We'll consider, that at the bottom of a vessel $y=Y_1$ medium oscillates with amplitude A, at the level $y=0$ being practically opposite in phase with amplitude G, and assume that in the interval $0<y<Y_1$ the removal changes linearly (y is counted off down from the level of air space). In other words, the case in point is standing wave with the node in point $0<y=GY_1/\left(A+G\right)<Y_1$. For such wave:

$$\Psi=\left(\frac{A+G}{Y_1}y-G\right)\omega^2,\qquad \Psi'=\frac{A+G}{Y_1}\omega^2$$ and,

according to the first part of formula (8) where X is replaced by Y,

$$V(Y)=-\frac{1}{2}\kappa^2\frac{\omega^2}{\omega^2+k_1^2}\frac{A}{Y_1}\left(z^2\frac{Y}{Y_1}-1\right)\frac{z^2}{\left(z^2-1\right)^2}A\omega^2, \tag{15}$$

$$\left(z>\sqrt{2}\right)$$

According to equation (7) the condition of particle detachment from the bottom is inequality $V\left(Y_1\right)+g\kappa<0$, which at the account of (15) takes the form

$$R\equiv\frac{1}{2}\kappa\frac{\omega^2}{\omega^2+k_1^2}\frac{A}{Y_1}\frac{z^2}{z^2-1}\frac{A\omega^2}{g}>1, \tag{16}$$

$$\left(z>\sqrt{2}\right)$$

The height of lifting a particle above the bottom of the vessel $h_*=Y_1-Y_*$, where Y_* – a coordinate of the quasiequilibrium point, defined from equation $V\left(Y_*\right)+g\kappa=0$.

As a result we found

$$h_*=Y_1\frac{z^2-1}{z^2}\frac{R-1}{R},\quad \left(z>\sqrt{2}\right) \tag{17}$$

It is easy to make certain, that this position of a particle is steady.

Observations and calculations on the reduced formulas show, that in conditions of our experiments the first model is realized. However, it's evidently that with rather different conditions the process goes according to the second model.

Note that in our experiments ratio ω_4/ω_2 turned to be equal to $220/190\approx 1{,}2$, which is rather lower than limiting theoretical value $\sqrt{2}$.

8. The "breakthrough" of an air "cushion" and self-oscillating cycle of system behavior

As it was noted in item 7, when air "cushion" reaches the certain volume corresponding value Z, exceeding a little $z=\sqrt{2}$, the growth of space stops, as the bubbles do not dip any more. The increase in this parameter due to the increase in frequency ω results, according to (12), in further decreasing of oscillations amplitude G of a fluid column. At some value $\omega=\omega_5$ and accordingly $z=\omega_5/\lambda$ (Fig. 2) amplitude decreasing G becomes so significant, that air is not kept any more by vibrational force near the bottom of the vessel, and it breaks upwards. This breakthrough can occur and with smaller values of z and ω if there are enough disturbances [Ganiev and Ukrainsky, 1975].

After the breakthrough of cushion at the fixed values of frequency ω in the certain range the whole cycle of system change repeats (in our experiments – each 2 – 3 s). In other words, so-called *asynchronous excitation of self-oscillations* takes place.

9. Conclusion

In the work the behavior of fluid – gas – solid body system in the vertically vibrating vessel has been experimentally studied. The effects of air bubbles dipping inside of fluid and floating particles, denser, than fluid and also self-oscillatory processes have been observed. For these effects, as well as for a classical system – a pendulum with a vibrating axis of suspension – the change of potential energy of system in a direction of maximum, instead of minimum, as in systems without vibration, is typical.

All these effects are physically explained and mathematically described on the basis of the united approach – vibrational mechanics and the method of direct separation of motions. Such approach leads to a rather simple differential equation of slow particle motions. The conditions providing bubbles dipping and floating of "heavy" particles follow from this equation.

Physical basis of all observed effects is the fact of fluid saturation at vibration with air bubbles and essential decrease in sound speed in such medium (up to 20 m/s). In turn specified saturation occurs as a result of peculiar lack of stability in a separate state of a fluid – gas system in the field of gravity. Such unstability occurs in conditions of rather intensive vibration with rather intensive disturbances – occurrence of the layer saturated with gas near the free fluid surface. One of the basic results of the given research is an explanation and mathematical description of this "vibrational" instability.

We have paid attention to the formation of the state of saturation with small air bubbles in vibrating fluid which can be named *as the phenomenon of a pseudosupercritical fluid occurrence*. The explanation and description of asynchronous excitation of self-oscillations has been given in system under vibration. So-called critical values of oscillation frequency at which there are qualitative changes in system behaviour have been introduced.

Dipping of bubbles and floating of “heavy” particles can be regarded as the effects of vibrational motion, conditioned by traditional type of asymmetry.

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