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Original Article

Computational Controlled Behavior of Gas Bubbles in a Fluid under Vibration Influence in the Conditions of Variable Gravity

M. Shoikhedbrod

Department of Electromagnetic Impulse Inc., 21 Four Winds Drive, Unit 12, North York, Ontario, Canada.

michaelshoikhedbrod@bell.net

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Abstract - The study of the dynamic behavior of gas bubbles in a fluid and the control of their behavior in a fluid under conditions close to weightlessness, using vibration effects, are important for solving several technological problems related to the needs of space technology (degassing of special fluids and fuel). The author, in a previously published article, considering vibration effects on air bubbles in an incompressible, non-viscous liquid located in a flat rigid vessel under conditions of variable gravity, obtained the conditions for the floating, sinking and oscillation of air bubbles around the equilibrium level in a fluid and the equilibrium level equation itself. In this article, the obtained equilibrium level equation was algorithmized, written in Turbo Basic computer language codes and compiled into an executable file. The result of the work of the obtained exe file was a numerical determination of the equilibrium level, around which the "swarm" of air bubbles oscillates, according to the corresponding vibration frequency at a given vibration acceleration, the volume of the "swarm" of air bubbles and the g-factor (an indicator of acceleration of gravity). For simulation on the screen of a personal computer, the movement of an air bubble or a "swarm" of air bubbles in an oscillating liquid in accordance with the calculated pairs, equilibrium levels and the corresponding vibration frequencies under conditions of a changing value of the g-factor (an indicator of acceleration of gravity) on the flying laboratory, an animation program was created, executed in the computer language Turbo C. The developed program allows synchronous modeling of the aircraft's trajectory (flying laboratory) when changing the value of the g-factor and the movement of an air bubble or a "swarm" of air bubbles when changing the vibration frequency in microgravity conditions. The flight tests conducted on board the IL-76K flying laboratory fully experimentally confirmed the theoretically obtained results.

Keywords - The g-factor and microgravity, Algorithm, Bubbles behavior under vibration influence, Computer modeling, Gas bubbles, Programmable languages.

1. Introduction

The study of the dynamic behavior of gas bubbles in a fluid and the control of their behavior in a fluid under conditions close to weightlessness, using vibration effects, are important for solving several technological problems related to the needs of space technology (degassing of special fluids and fuel) [1 - 6]. The author in a previously published article [7], considering vibration effects on air bubbles in an incompressible, non-viscous liquid located in a flat rigid vessel under conditions of variable gravity, obtained the conditions for the floating, sinking and oscillation of air bubbles around the equilibrium level in a fluid and the equilibrium level equation itself:

$a(\alpha N-2)+\frac{12\sigma_{12}}{\rho a^2\lambda^2}<0$ - bubble's floating;

$a(\alpha N-2)+\frac{12\sigma_{12}}{\rho a^2\lambda^2}>0$ - bubble's sinking; (1)

$a(\alpha N-2)+\frac{12\sigma_{12}}{\rho a^2\lambda^2}=0$ - bubble's fluctuations around the equilibrium level.

Here, $\alpha = \frac{3Ngh}{a^2(\lambda^2-\acute{\omega}^2)}$

$$h_{eq} = \frac{P_0}{\rho n g_0\left[\frac{N^2\lambda^2}{2\nu\left(1-\frac{6\sigma_{12}}{\rho\lambda^2 a^3}\right)(\lambda^2-\acute{\omega}^2)}-1\right]} \quad (2)$$

Where h - the level on which the is located bubble; $\acute{\omega}$ - the vibration frequency; Ng_0 - the vibration acceleration of the vibration stand; λ - frequency of the small bubble of radius (a) vibration; h_{eq} - the equilibrium level; ν – the polytrophic constant; g_0 - the acceleration of gravity, equal 980 cm/c^2; P_0 - the pressure above fluid air shell; n - g-factor; σ_{12}.- surface tension on the boundary phases gas-fluid.

In this article, the obtained equilibrium level equation was algorithmized, written in Turbo Basic computer language codes and compiled into an executable file. The result of the work of the obtained exe file was a numerical determination of the equilibrium level, around which the "swarm" of air bubbles oscillates, according to the corresponding vibration frequency at a given vibration acceleration, the volume of the "swarm" of air bubbles and the g-factor (an indicator of acceleration of gravity).

For simulation on the screen of a personal computer, the movement of an air bubble or a "swarm" of air bubbles in an oscillating liquid in accordance with the calculated pairs, equilibrium levels and the corresponding vibration frequencies under conditions of a changing value of the g-factor (an indicator of acceleration of gravity) on the flying laboratory, an animation program was created, executed in the computer language Turbo C. The developed program allows synchronous modeling of the aircraft's trajectory (flying laboratory) when changing the value of the g-factor and the movement of an air bubble or a "swarm" of air bubbles when changing the vibration frequency in microgravity conditions. The flight tests conducted on board the IL-76K flying laboratory fully experimentally confirmed the theoretically obtained results

2. Materials and Methods

Flight tests for confirmation of the theoretical results of the computational controlled behavior of gas bubbles in a fluid under vibration influence in the conditions of variable gravity simulation were conducted on board the Il-76K flying laboratory aircraft [8]. The change of the value of the g-factor (acceleration gravity) depending on the flight time of the Il-76K flying laboratory aircraft was created by moving it along a special parabolic trajectory (Kepler parabola), the shape of which was close to the flight trajectory to a stone at an angle to the horizon.

For experimental confirmation of the theoretical results of the computational controlled behavior of gas bubbles in a fluid under vibration influence in the conditions of variable gravity simulation, a hermetically sealed cylindrical vessel made from organic glass, a vibration stand and water were used. Based on the obtained Equation (2), an algorithm was developed, written in the codes of the computer language Turbo Basic and compiled as an exe file of the program calculation, which numerically simulated the dependence of the equilibrium level on the vibration frequency ω, acting on the entire system, with constant values of the g-factor (n), the volume of the "swarm" of air bubbles and vibration acceleration.

For the development of the algorithm, Equation (2) was transformed into a new form, in which the dependence of the equilibrium level h_{eq} on the value of the g-factor (n) and the vibration frequency becomes explicit since λ^2 in Equation (2) is equal to $(3\nu P_1)/(\varrho_{fl} a^2)$, and $P_1 = P_0 + \varrho_{fl}\, n g_0\, h_{eq}$.

For this, λ^2 was substituted as $(3\nu\ (P_0+\varrho_{fl} n g_0 h_{eq}))\ /\ (\varrho_{fl} a^2)$ in Equation (2) and the resulting equation was resolved with respect to the root h_{eq}. As a result, the equation for calculating h_{eq} is as follows:

$$h_{eq} = (-1)\ (K_2/2K_1) - (\sqrt{K_2{}^2 - 4K_1K_3}\ )\ /\ 2K_1 \qquad (3)$$

Where,

$K_1 = 9\varrho_{fl}{}^2 a\, n^3 g_0{}^3 (N^2 - 2)$;
$K_2 = 6\varrho_{fl}\, n\, g_0{}^2 (3P_0\, a\, (N^2 - 2) + 6\, \sigma_{12} + \varrho_{fl}\, a^3\omega^2)$;
$K_3 = 3ng_0 (2P_0 (6\sigma_{12} + \varrho_{fl}\, a^3 + \omega^2) - 4\varrho_{fl}\, a^2\, \sigma_{12}\, \omega^2 - \varrho_{fl}\, a^3 P_0)$;
$P_0 = \varrho_{air}\, n g_0 L$

Here ϱ_{fl} - the water density, equal 1 g/cm^3; a - the radius of the bubble or "swarm" of the air bubbles; g_0 - the Earth's acceleration of gravity, equal 980 cm/sec^2; N - the vibration acceleration of the vibration stand, equal 150 m/sec^2 or 15000 cm/sec^2; ω - the vibration frequency; n - the amount of g-factor; ϱ_{air} - the air density, equal 0.00019 g/cm^3 and L - the above liquid shell column height in the vessel, accepted in the calculations as 2 cm. Figure 1 depicts the printout of the program's calculation constants and data input on the computer screen.

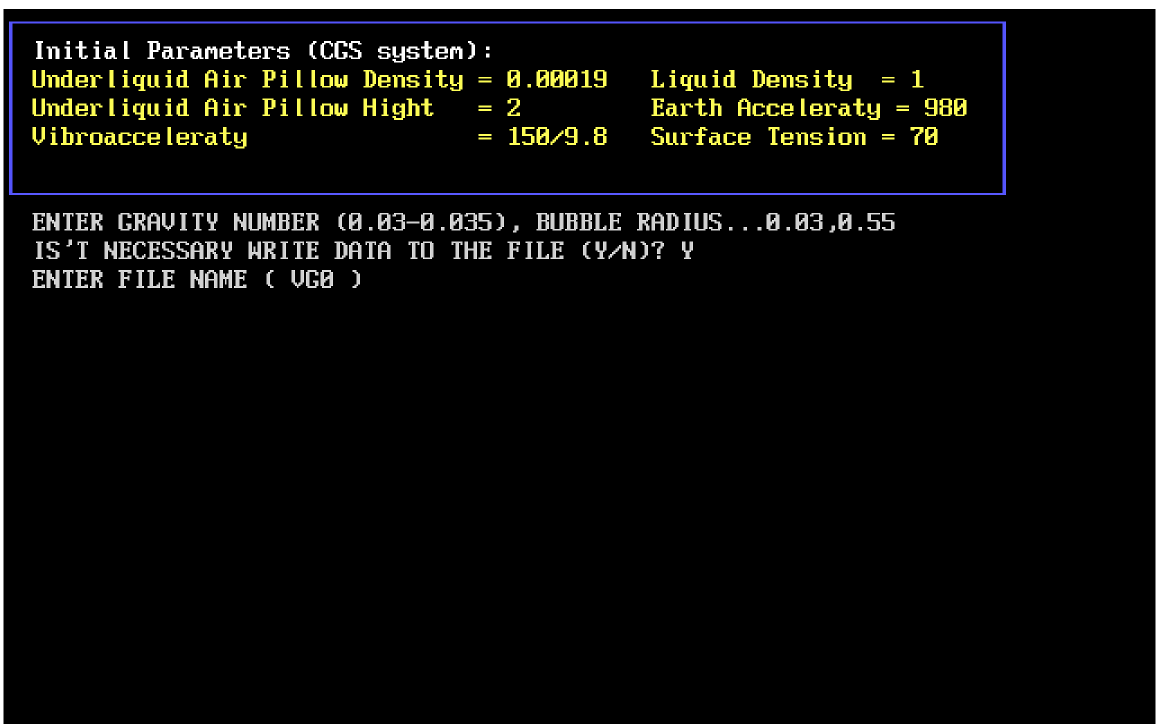

Fig. 1 Printout on the computer screen of the program data input

Figure 2 depicts the printout of the program of the numerical simulation of the dependence of the equilibrium level of h_{eq} of air bubble or "swarm" of air bubbles, by a radius 0.55 cm, by the volume 0.7 cm^3, on the frequency of vibration in the range of frequencies ω from ω = 18 Hz to 540 Hz by step of 18 Hz under g-factor of n, equal 29.40 cm/sec^2 (or 0.03 un.) and vibration acceleration, equal 150 m/sec^2 or 15000 cm/sec^2.

For simulation on the screen of a personal computer, the computationally controlled behavior of gas bubbles in a fluid under vibration influences the conditions of variable gravity. An animation program was created and executed in the computer language Turbo C. For entering data into the animation program, in the computer program calculation, numerically calculating in accordance with Equation (2) the dependence of the equilibrium level h_{eq} on the value of g-factor (n) and the vibration frequency ω, acting on the entire system: "swarm" of air bubbles + fluid + vessel, described earlier, it was provided to record in the file "VG0" the total number (MI) of pairs of vibration frequencies and the corresponding equilibrium levels, the value of the vibration acceleration (N1), the volume of the air bubble or "swarm" of air bubbles (VOL), pairs of vibration frequencies and the corresponding equilibrium levels.

H Level	Frequentcy	Gravity	Volum
-0.3168	18.00	29.40	0.697
-0.6049	36.00	29.40	0.697
-0.9028	54.00	29.40	0.697
-1.2103	72.00	29.40	0.697
-1.5275	90.00	29.40	0.697
-1.8545	108.00	29.40	0.697
-2.1915	126.00	29.40	0.697
-2.5387	144.00	29.40	0.697
-2.8962	162.00	29.40	0.697
-3.2644	180.00	29.40	0.697
-3.6434	198.00	29.40	0.697
-4.0334	216.00	29.40	0.697
-4.4346	234.00	29.40	0.697
-4.8471	252.00	29.40	0.697
-5.2711	270.00	29.40	0.697
-5.7070	288.00	29.40	0.697
-6.1547	306.00	29.40	0.697
-6.6145	324.00	29.40	0.697
-7.0866	342.00	29.40	0.697
-7.5711	360.00	29.40	0.697

H Level	Frequentcy	Gravity	Volum
-8.0682	378.00	29.40	0.697
-8.5780	396.00	29.40	0.697
-9.1008	414.00	29.40	0.697
-9.6367	432.00	29.40	0.697
-10.1857	450.00	29.40	0.697
-10.7482	468.00	29.40	0.697
-11.3242	486.00	29.40	0.697
-11.9138	504.00	29.40	0.697
-12.5172	522.00	29.40	0.697
-13.1345	540.00	29.40	0.697

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-9.6367	432.00	29.40	0.697
-10.1857	450.00	29.40	0.697
-10.7482	468.00	29.40	0.697
-11.3242	486.00	29.40	0.697
-11.9138	504.00	29.40	0.697
-12.5172	522.00	29.40	0.697
-13.1345	540.00	29.40	0.697

Fig. 2 Printout of the program of the numerical calculation of the dependence of the equilibrium level h_{eq} of the "swarm" of the air bubbles on the frequency of vibration in the range of the frequencies of vibration from ω = 18 Hz to 540 Hz with the step 18 Hz

The sequence of launching the calculation program, writing one file to the folder containing the animation program, reading data from one file by this program, and synchronous animation of the behavior of an air bubble or a "swarm" of air bubbles in a vibrating liquid under microgravity conditions and the flight trajectory of the Il-76K flying laboratory under conditions of a changing value of the g-factor on the computer screen was carried out by launching the virbo.bat file with the following contents:

```
@echo off
tbvibro -calculation program
tcvibro -animation program
```

Equation (2) shows that with $n \to 0$, $h_{eq} \to$ to the infinity, and since the column of liquid is limited by the bottom of the vessel, then with $n \to 0$, we will obtain $h_{eq} \to L$, where L - the column of liquid height in the vessel. Thus, the air bubble or "the swarm" of air bubbles, which is oscillated near the steady equilibrium level, under the influence of vibration, in the case of decreasing of the acceleration of gravity g from g = 980 cm/sec^2 to g = 0 (or g-factor n = 1 un. to g-factor n = 0), has to descend in the direction to the bottom of the vessel and reach it at g = 0.

Figure 3 demonstrates the screenshots (stills) of the developed animation computer program work, simulating the behavior of a gas bubble in the fluid under the influence of vibration with a constant frequency of 108 Hz. and the constant vibration acceleration 16, in the conditions of the acceleration of gravity decrease from g = 980 cm/sec^2 (g-factor n = 1un) to g = 29.40 cm/sec^2 (g-factor n = 0.03).

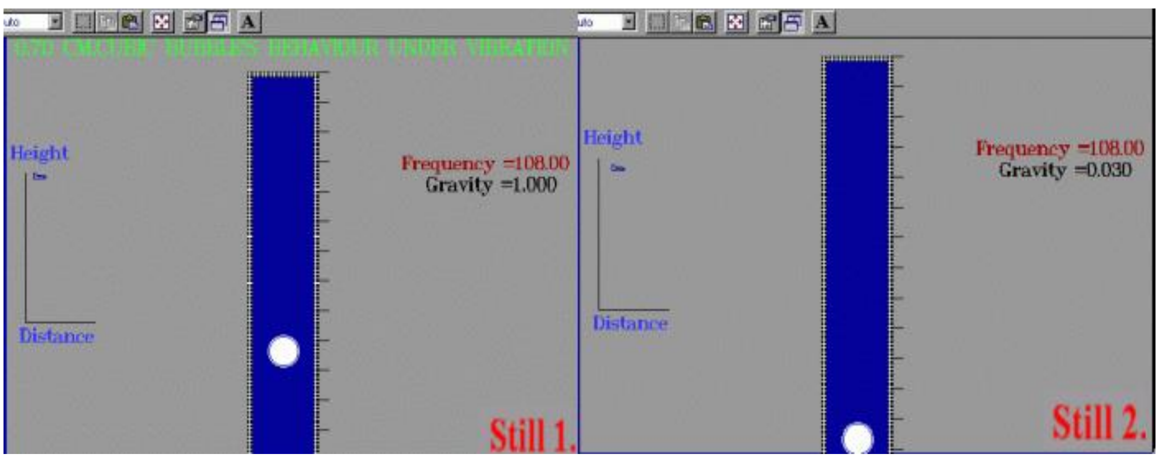

Fig. 3 The screenshots-stills of the developed animation computer program work, simulating the gas bubble behavior in the fluid under the influence of vibration with a constant frequency of 108 Hz. and the constant vibration acceleration 16 in the conditions of the acceleration of gravity decrease from g = 980 cm/sec^2 (g-factor n = 1un.) to g = 29.40 cm/sec^2 (g-factor n = 0.03)

Equation (2) clearly shows that, just as in the Earth case, with the decrease of the frequency of vibration ($\acute{\omega}$), the equilibrium level (h_{eq}) increases (direction of equilibrium level is counted from the free surface of fluid to the bottom of the vessel) and the "swarm" of bubbles descends, and with an increase of the frequency of vibration ($\acute{\omega}$), equilibrium level (h_{eq}) decreases and the "swarm" of bubbles rises.

Consequently, just as in the Earth's case, the "swarm" of bubbles in the fluid under the conditions of microgravity can be controlled by using a change of the frequency of vibration ($\acute{\omega}$), and the obtained Equation (2) makes it possible with the calculated accuracy.

Figure 4 demonstrates the screenshots-stills of the developed animation computer program work, simulating the raising of gas bubbles with an increase of the vibration frequency from 216 Hz to 414 Hz, with the constants vibration acceleration 16 and the acceleration of gravity g = 29.40 cm/sec^2 (g-factor n= 0.03 units).

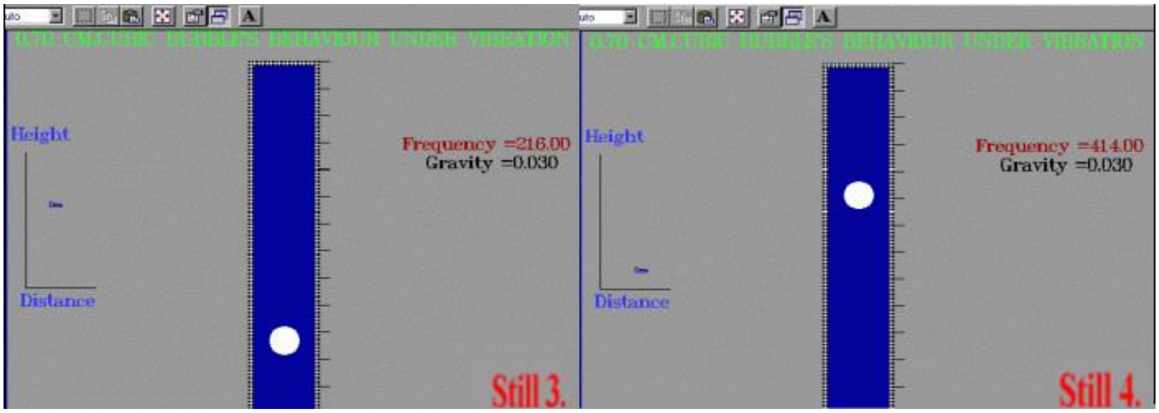

Fig. 4 The frames-stills of the developed animation computer program work, simulating the rising gas bubbles with an increase of the vibration frequency from 216 Hz to 414 Hz at the constants vibration acceleration 16 and the acceleration of gravity g = 29.40 cm/sec² (g-factor n= 0.03 un.)

3. Results and Discussion

The flight tests conducted on board the IL-76K flying laboratory fully experimentally confirmed the theoretically obtained results. Figure 5, like Figure 3, illustrates the frames of filming of the results of flight tests that show the dependence of the positions of the equilibrium level of gas bubbles in the conditions of the acceleration of gravity decrease from g = 980 cm/sec ² to g = 0 with the constant frequency of vibration 108 Hz and the constant vibration acceleration 16.

Figure 6, like Figure 4, illustrates the frames of filming obtained as a result of the flight tests, which show raising gas bubbles with an increase of the vibration frequency from 216 Hz to 414 Hz at the constants vibration acceleration 16 and the acceleration of gravity g = 29.40 cm/s ² (g-factor n= 0.03 un.).

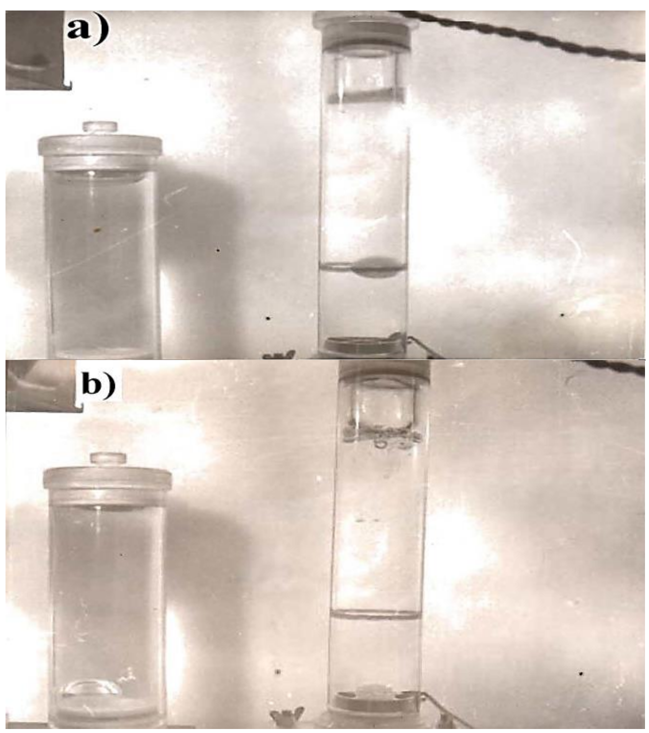

Fig. 5 Frames of the filming of results of flight tests that show the dependence of the positions of the equilibrium level of gas bubbles on the decrease of the acceleration of gravity from g = 980 cm/sec² to g = 0 with the constant frequency of vibration 108 Hz and the constant vibration acceleration 16 a) - g = 980 cm/sec²; b) - g = 0

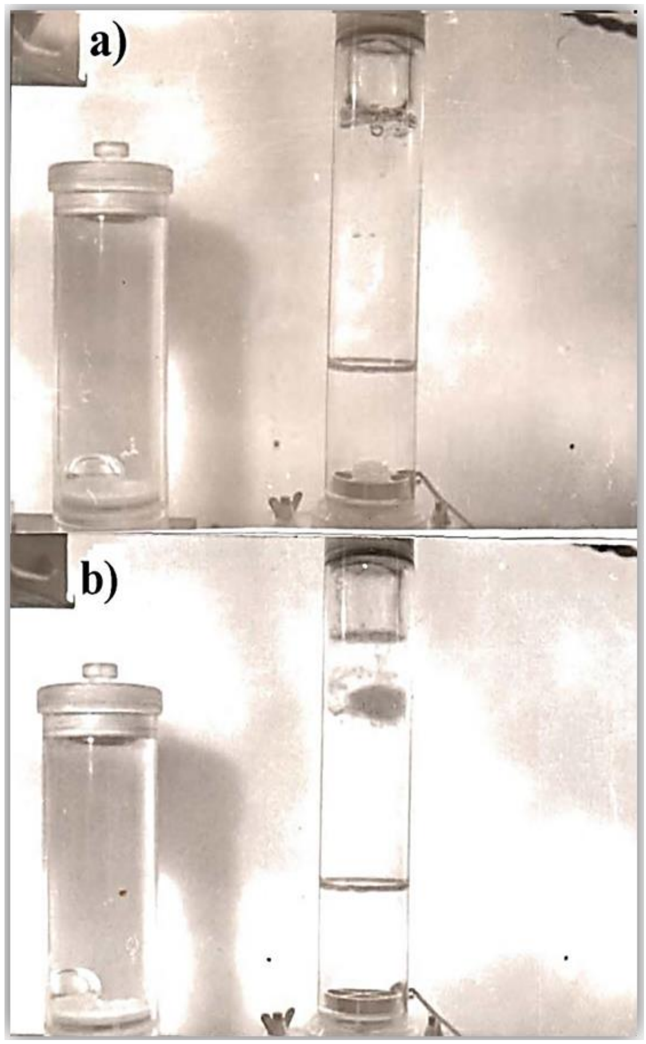

Fig. 6 Frames of filming, obtained as a result of the flight tests that show raising gas bubbles with an increase of the vibration frequency from 216 Hz to 414 Hz, at the constants vibration acceleration 16 and the acceleration of gravity g = of 29.40 cm/s ² (g-factor n= 0.03 un.) a) ώ = 216 Гц, and b) ώ = 414Гц.

4. Conclusion

The equilibrium level equation, obtained earlier by the author, was algorithmized, written in the computer language Turbo Basic codes and compiled into an executable file: a calculation program. The result of this program was the numerical determination of the equilibrium level around which the "swarm" of air bubbles oscillates, according to the corresponding oscillation frequency for a given vibration acceleration, the volume of the "swarm" of air bubbles and the g-factor (an indicator of acceleration due to gravity).

For simulation on the screen of a personal computer, the movement of an air bubble or a "swarm" of air bubbles in an oscillating liquid in accordance with the calculated pairs: equilibrium levels and the corresponding oscillation frequencies under conditions of a changing value of the g-factor (an indicator of acceleration of gravity), an animation program, executed in the computer language Turbo C, was created. The developed program allows synchronously simulating the aircraft's trajectory (flying laboratory) when the value of the g-factor changes and the movement of an air bubble or a "swarm" of air bubbles when the oscillation frequency changes in microgravity conditions. Flight tests conducted on board the Il-76K flying laboratory fully experimentally confirmed the theoretical results obtained.

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