

E. M. Agrest and G. N. Kuznetsov

**THE ORIGINATION AND DEVELOPMENT OF ULTRASONIC CAVITATION ON  
VARIOUS FORM OSCILLATORS**

Johnson & Wales University  
701 East Bay Street, Charleston, SC 29403, USA  
Phone: 843-727-3009 (office)  
E-mail: [Emmanuel.Agrest@jwu.edu](mailto:Emmanuel.Agrest@jwu.edu)

Wave Research Center of the General Physics Institute RAS  
38 Vavilov street, 117942 Moscow, Russia  
Phone: (095) 256-1790  
E-mail: [kuznetsovgn@mtu-net.ru](mailto:kuznetsovgn@mtu-net.ru), [skbmt@mail.ru](mailto:skbmt@mail.ru)

*An analysis of cavitation nucleus (gas bubbles in sound fields, generated by various forms oscillators) dynamics is presented. Some general regularity caused by interactions of cavitation nucleus with inhomogeneous sound fields with alternative pressure gradients are stated. It is concluded that the main mechanism of the inception of the earlier stage of cavitation is caused by Bierkness and pressure gradient based coagulation of cavitation nucleus, which pulsate in their translating motion in inhomogeneous sound fields. The important role of convective diffusion is noted. The acoustic effects, on appearance of which is recorded the cavitation threshold, are caused by the loss of the dynamic stability of pulsatory and increasing their average size bubbles-embryos of cavitation.*

Pressure pulsations in liquids produced by various piezoceramics or magnetostriction oscillators are the sources for the inception of ultrasonic cavitation on the surfaces as well as in the sound concentration areas. The results of experimental studies of cavitation bubbles and cavitation region in the areas of cylindrical concentrators, round axisymmetric piezoceramics pistons, membranes, and concentrators with a conical nozzle are discussed below. A long focus lens filming with a stroboscopic lighting performed the experimental studies. The cavitation noise was recorded by hydrophones located beyond the cavitation zone. The liquid was a 10% mixture of water and glycerin. Filming was conducted under normal atmosphere pressure  $P_0$  in gas-saturated liquids and in vacuum treated liquids. The threshold of cavitation was indicated by well-known acoustical [1] and also visual features. The peculiarities of the ultrasonic cavitation threshold results will be discussed below.

1. **Cavitation in the focusing region of a hollow cylindrical concentrator** (the frequency  $f = 7.3$  kHz) takes place in a rather homogeneous pressure field in the axe of symmetry direction and cosine type in radii. When the pressure amplitude increases to the value of approximately  $0.5 P_0$  to  $0.6 P_0$  gas cavities are visualized in the central region of a concentrator, those bubbles with the radius of  $R_0$  are moving towards the antinode of the pressure while performing radial oscillations. The average translation velocity depends on the radius,  $R_0$  and the amplitude of the ultrasonic pressure  $P_m$  and was recorded as approximately 10-20 cm/sec. Two bubbles, when approaching the distance less then  $\Delta r \sim 10R_0$ , they coagulate, forming a larger cavity that moves faster towards the antinode. Those cavities grow to the size of about 5 to 10 time smaller than the resonance size,  $R_*$ . One can observe harmonic components in the spectrum of cavitation noise, i.e. even stable, less than resonance-size bubbles after a vile will pulsate nonlinear and result in none harmonic pressure in the area of the antinode. While the ultrasonic pressure amplitude,  $P_m$  increases the failure of the dynamic stability [2] takes place and pressure impulses recorded by hydrophones. Intensive compression may occur on every second or the third pulsation and one may record not only harmonics but also sub-harmonics of the main ultrasonic frequency [1]. When the amplitude increases to  $P_m \sim P_0$  bubbles of the average during the pulsation period size of  $R_*$  and even greater are registered in the area of the antinode. This results in their evacuation from the antinode area towards the surface of the concentrator. Reciprocating migration towards the antinode and back of the same bubble takes place.

2. **Cavitation on the oscillating piston surface or on the membrane.** The pressure distribution over the surface of a piston is usually rather uniform, but because of the boundary conditions on the edge of a piston the pressure in the center of the piston may differ from that of on the edge up to two times. There is a radial inhomogeneous in the pressure field. Origination of cavitation was studied at the piston oscillation frequencies of 7,8 and 8,9 kHz in same liquids and other conditions as described in paragraph 1. While the ultrasonic pressure increases, the signal on the hydrophone becomes nonlinear i.e. sub-harmonics of the main frequency may be observed. Further increases in pressure produces visible gas bubbles. Solid boundary conditions, as it is well known, result in attracting bubbles to a surface, but they still perform radial motions towards the center – antinodes. While moving some of bubbles may coagulate. If the sound amplitude increases or for the longer period of time larger bubbles will occur, with size close to resonance. These cavities are pulsating more intensively and radiate harmonic and sub harmonic components. Rapid collapse results in shock wave generation and cavities scattering into a number of small bubbles. In some cases large cavities were released from the central zone with a velocity much greater than others that were moving towards the center. Increasing of the ultrasonic field amplitude ( $P_m \geq P_0$ ) changes the picture. Cavities, randomly originating near the surface of the piston move toward the center, coagulate forming an over-resonance bubble that due to counter-faze pulsations changes the direction of the motion to opposite and rapidly leave the central portion of the piston. This process becomes almost periodic. While moving away from the surface a cavity carries a lot of small bubbles along itself. The cloud of bubbles looks like a comet: a lot of small bubbles attracted by a big one are not able to catch up with a rapidly moving big bubble and they look like a train of a comet. Bubbles of sizes much bigger than the resonance were not observed because they would break down into smaller bubbles that will move away in opposite direction.

**Cavitation near the tip of the conical concentrator.** Experiments were conducted at the atmospheric fluid pressure with the parameters, identical to those preceding. Operating frequency of concentrator 18.2 kHz. It was impossible to measure the value of pressure in the zone of the appearance of cavitation, since this zone is very small and the pressure field is very nonhomogeneous. The form of cavitation region and the voltage, with which cavitation noise appeared, depended substantially on the form of the concentrator tip. With the needle-shaped extremity predominantly the single bubbles appeared, which are formed and are compressed as in the hydrodynamic field during the flow for different shape bodies. Sufficiently high-frequency pressure impulses appear randomly. The adjacent cylinder ring-shaped zone of cavitation (in the vortices) is formed with the cylindrical extremity with the flat round end with a diameter of 3 mm. In the spectrum of cavitation noise two washed away maximums are observed: one in the zone of the fundamental ripple frequency of pressure (18.2 kHz), the second (smaller in the level) it was formed at frequencies of 2.8-3 kHz. With an increase double the diameter of the terminal cylinder (6 mm) the frequency of this maximum was lowered 1.8 times. This does testify about the connection of this phenomenon with the kinematic similarity criterion - Strouhal number  $St = Fd/V$ , where  $F$  - the frequency of maximum in the spectrum,  $d$  - linear transverse dimension,  $V$  - the speed of the flow. Confirmation of this model is the presence of hysteresis of the cavitation threshold, which was also observed for the cavitation in the vortex in previous studies. With the developed form of cavitation just as in the foregoing cases is observed the intensive ejection of cavities from the region of the cavitation. I.e., are observed the phenomena, analogous by that presented above, since there are alternating gradients and the pulsation of the cavities of subresonance and transresonant sizes.

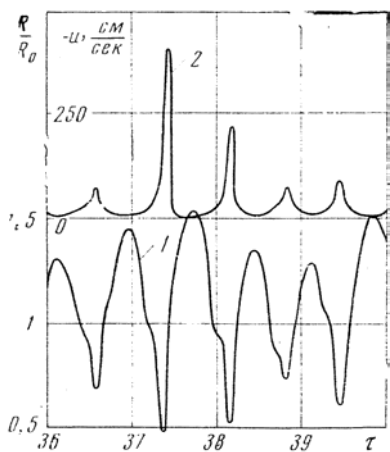
3. **The calculational-theoretical analysis** of the behavior of gas embryos of cavitation in weak and moderate heterogeneous acoustic fields is made in a series of works [ 3-6 ]. The system of equations of radial and forward motion is examined in the form [ 4 ].

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2\sigma}{R} - \frac{1}{\rho} \left[ \left( P_0 + \frac{2\sigma}{R_0} \right) \left( \frac{R_0}{R} \right)^3 + P_H \right] - \frac{1}{4}u^2 = -\frac{1}{\rho}(P_0 + P_m \varphi \sin \omega t) \quad (1)$$

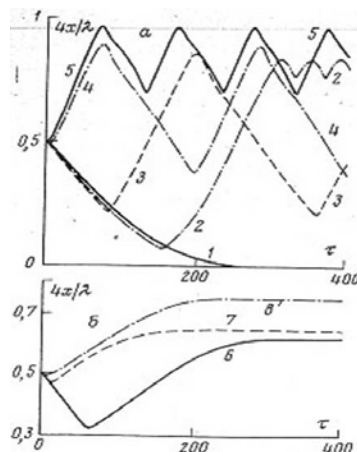
$$\frac{d}{dt} \left[ \rho' V \bar{u} + \frac{1}{2} \rho V (\bar{u} - \bar{v}) \right] = -D(\bar{u} - \bar{v}) - V \nabla P \quad (2)$$

where  $R$  and  $R_0$  are the current and initial radii of gas bubble,  $\varphi(r) = \varphi(Z/L)$  is a function, which characterizes the heterogeneity of acoustic field of the scale  $L$ ;  $\omega$  is the angular frequency,  $\sigma$  is the coefficient of surface tension,  $\rho', \rho$  are the density of gas and liquid,  $V$  is the volume of the bubble,  $\vec{u}$  is the velocity vector of forward motion of the bubble,  $\vec{v}$  is the velocity vector of liquid,  $\nabla P$  is the gradient of sound pressure.

The drag coefficient, which characterizes liquid resistance to translational motion of the bubble, is used as in [2].  $D = 6\pi\mu R \left[ 1 + 0.065 \text{Re}^{2/3} \right]^{1/3}$  where  $\text{Re} = \frac{2\rho R|\vec{u} - \vec{v}|}{\mu}$  is the Reynolds number,  $\mu$  is the viscosity of liquid. Calculations did show that “subresonance” cavities  $R_0 < R_*$ , which are located in the oscillating gradient field, are moved on the average during the period towards the antinode of pressure (into the zone of maximum pressure), and transresonant ( $R_0 > R_*$ ) are moved towards the pressure nodes. In the contraction phase the cavity rapidly decreases in the size and the speed of forward motion sharply increases.



**Fig. 1** The top curve is the translational velocity versa time (in ultrasonic periods), the bottom is relative radius versa time.



**Fig. 2.** Movement of different cavities in the time. Zero along the Y-axis corresponds to the antinode of pressure. Curves 1-8 correspond  $100R_0 = 1.9; 1.93; 1.97; 2.03; 2.29; 1.12; 1.14; 1.22$  cm.

Fig. 1 gives [ 4 ] the dependences of relative radius  $R/R_0$  (1) and speed of translational motion (2) versa the time ( $\tau$  - the number of period). It is evident that during the nonequilibrium compression of cavity the maximum of translational motion velocity,  $U_{\max}$  substantially exceed speed average during the period. Calculations also showed that translational motion strongly affects the speed of compression, for example, if a fixed in space cavity is compressed at a velocity, close to the speed of sound in the water, then because of forward motion the speed of compression decreases about ten times. It is established also, that the monotonic tendency into the zone of maximum pressure is characteristic only for the weakly-pulsatory “subresonance” cavities ( $R_0 < R_*$ ). In the case of transresonant cavities ( $R_0 > R_*$ ) with  $R_0 > R_*$  or for the intensively pulsatory cavities  $R_0 > R_*$ , but  $R_{\max} \gg R_0$  and  $R_{\max} > R_*$  bubbles pulsate in the reversed phase with the pressure and pressure gradient ejects them at a high speed from the zone of pressure maximum. Small bubbles with the sizes  $R_0 < R_*$ , but pulsating in the moderate field of sound pressure, in the zone of pressure maximum ( $P_m \approx P_0$ ) intensively behave similarly to transresonant cavities since the nonlinear effects and since  $R_{\max} > R_*$ , while far from the antinode they behave as “subresonance” cavities ( $R_0 < R_*$ ). As a result, for these cavities can be observed the alternation of the direction of migration to the antinode of pressure and then to the knot and vice versa to the antinode, that also is observed experimentally. The

zones of localization and the period of migration in one direction depend both on the value of  $R_0$  and on values of  $P_{\max} / P_0$ . An example of such displacements is given in Fig. 2 [ 6 ]. In [ 4 ] is obtained analytical relationship for the instantaneous and average speed of translational motion of the stably pulsatory cavity. The average velocity can be calculated for  $R_0 < R_*$ ,  $P_m < P_0$  as  $U = A + B\delta$ ,

$$\text{where } A = -\frac{P_m}{2\pi} \frac{d\varphi}{dr} + \frac{P_0}{\pi q} \cdot \frac{dl_u \varphi}{dr} \left( 2 + \pi - 3\pi q - 2 \arctg \frac{P_m \varphi}{P_0 q} \right) ; \quad B = 2P_0 \frac{dl_u \varphi}{dr} \left( \frac{1}{q} - 1 \right) ; \quad q = \sqrt{1 - \frac{P_m^2}{P_0^2} \varphi^2} .$$

Calculations show that in the water the average velocities of translational motion in the steady part of the flow reach 10-20 cm/s. I.e., cavity is capable of passing, for example, 1-2 cm for 0.1 s, which for the frequency of 10 kHz corresponds to a quantity of periods  $\tau = 10^3$ , which corresponds to the experiments. The calculations of the dynamics of the function of the bubble distribution according to the sizes in the nonuniform fields of pressure showed that under the action of pressure gradient the cavities are collected sufficiently rapidly from the entire volume into the antinode of pressure. This process contributes to their coagulation and we call this process the “gradient coagulation” [5]. It is obvious that with translational motion the diffusion processes are intensified. Because of an increase in the density of embryos an intensive Bierkness coagulation of embryos of cavitation takes place and are formed the large cavities [ 7 ], which as a result of the loss of dynamic stability begin to pulsate nonlinearly even with  $P_m < P_0$  [ 2 ]. All this is confirmed well experimentally. Thus independent of the structure of acoustic field on the emitters, “gradient” and “Bierkness” coagulation together with the convective diffusion convert invisible stable micro-embryos of cavitation (dispersed phase) into the unstable cavities. Dynamic stability is lost, nonlinear pulsations appear, as well as shock waves, noise and erosion.

#### REFERENCES

1. Akulichev V.A. Pulsation of cavitation cavities. In the book: Powerful ultrasonic fields. M., Science. 1968. p. 129-166 (physics and powerful ultrasound technique; Vol. 2).
2. Kuznetsov G.N. The dynamic strength of liquid. In the collection: Acoustics and ultrasonic. Iss. 111. Kiev. Technology, 1976. p. 3-7.
3. Crum L.A., Eller A.I. Motion of Bubbles in a Stationary Sound Field // J. Acoust. Soc. America, 1970. 48. 1. PP. 181-189
4. E.M. Agrest, G.N. Kuznetsov. Instantaneous parameters of the motion of a cavitation bubble in an inhomogeneous sound field. Sov. Phys. Acoust., Vol. 19, No. 3, 212-215, 1973.
5. E.M. Agrest, G.N. Kuznetsov. Dynamics of the bubble distribution in sound fields. Sov. Phys. Acoust., Vol. 20, No. 3, 213-216, 1974.
6. E.M. Agrest, V.L. Korets. Large-scale spatial oscillations of a cavity in a sound field. Sov. Phys. Acoust., Vol. 24, No. 1, 1-5, 1978.
7. Kuznetsov G.N., Shchekin I.E. The influence of coagulation and gas diffusion on the cavitation strength of liquid. Sov. Phys. Acoust., Vol. 21, No. 5, 1975