RAREFACTION WAVES AND BUBBLY CAVITATION IN REAL LIQUID

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Abstract

The paper presents the short review of two stages of cavitating liquid fracture at the explosive loading. The problems of the real liquid state (with view point of its inhomogeneity) and limit tensile stress, as well as the mechanics of the cavitation development excited by intense rarefaction waves and the dynamic feature of breaking of a spherical liquid drop under the action of ultra-short shock wave are considered.

1 Introduction

The problem of liquid fracture in intense rarefaction waves at explosive loading of a liquid volume with a free surface is often connected with a liquid strength conception having in view a conception of a critical tensile stress p_c admitted by the cavitating liquid. Two results of liquid strength studies can be mentioned. This is the measurement of a dome velocity $v = (2p - p_c)/\rho D$ at shallow underwater explosions when it tends to zero (see Wilson et al. 1975). Critical pressure value p_c for settled tap water turned out to be -0.85 MPa, for deionized and vacuumized water - 1.5 MPa. The second result was received at high velocity loading and has shown the value p_c = -60 MPa in Carlson and Henry (1973). One can see that these data are essentially different and depend on both a liquid state and a dynamics of loading.

Practically in all the experiments these data are associated with a visible breaks in liquid (cavities), which develop on cavitation nuclei when affected by intense rarefaction waves. However the mentioned conception of a critical tensile stress p_c restricts essentially the understanding of the complicated process of fracture. This process may be defined as an effect of inversion of a two-phase state of medium consisting in transformation of cavitating liquid in a gas-droplet system. The inversion scheme involves a number of stages such as formation of bubble clusters, its transformation in a structure of a foam type with a following fracture into cavitating fragments, transition to the droplet state and its evolution.

2 State of real liquids and relaxation effects

Being the most investigated this section deals with such problems as a state of a real liquid, conception of liquid strength, formation mechanism of bubble clusters as well as its mathematical simulation. Real liquid structure in macroscale is such that even after special purifications, distillation and deionization there are a lot of microinhomogeneities, which play the role of cavitation nuclei : fluctuating holes (Frenkel'), hydrophobic particles with nuclei in crevices (Harvey), nuclei as solid particles (Plesset), combination structures of free gas microbubbles and solid microparticals (Besov, Kedrinskii, Pal'chikov) (see Kedrinskii 1993).

The experimental data shows that in fresh distilled water the maximum of bubble size in a spectrum is approximately on the level of 4 μm, in settled water - 0.85 μm (Kedrinskii 1993). Experimental results on bubble spectrum in settled water (see Hammit et al. 1976) and their generalization in Kedrinskii (1985) allowed to estimate the total density of microinhomogeneities: ($N \simeq 10^5 \div 10^6\ cm^{-3}$). This magnitude correlates with the estimation obtained from track registration of diffraction spots arising at the light scattering on the microinhomogeneities of any nature.

The results on acoustic diagnostics of free gas microbubbles, denoting their extremely low density served as the basis of mechanism of avalanche-type "settlement" of the developing bubble cavitating zone by the nuclei (see Sirotyuk 1968). It is caused by the instability of nuclei shape, its intense growth and collapse. However, the development of dense cavitation zone in a field of a single rarefaction pulse (for example at underwater explosion near free surface) cann't be explained by means of the above mentioned scheme.

According to the new mechanism of cavitation zone development suggested in Kedrinskii (1986) a real liquid is considered to contain a wide spectrum of cavitation nuclei in the range of sizes $R_0 \simeq 10^{-3} \div 10^{-7} cm$ at a concentration $k_0 \simeq 10^{-8} \div 10^{-12}$. The concept of visible, i.e. detectable size of cavitation bubble is introduced. The mentioned effect of cavitation zone "settlement" in relatively weak ultrasonic fields is explained by gradual saturation of a zone by the detectable bubbles, which attained the visible size over different time intervals in the dependence on their initial position in spectrum.

The data presented enable to interpret the real liquid state as a state of two-phase medium despite the insignificant initial gas content (volume concentration). In this case it is natural to suppose that a transformation mechanism of rarefaction waves in cavitating liquid is similar to known effects on the shock wave propagation in bubble media and to use the mathematical model of bubbly liquid for the description of cavitation effects (see Kedrinskii 1976). This model is a system of conservation laws, written for average density ρ, pressure p and mass velocity u. According this model a system of conservation laws is closed by some subsystem including the Rayleigh's type equation for the volume concentration of vapor-gas phase k and by the relation of $\rho(k)$. If the liquid component is incompressible the mentioned system can be reduced to the form (axisymmetrical case)

$$\Delta\xi = \xi, \qquad k_{tt} = -\frac{3k^{1/3}}{\rho_0 R_0^2} \cdot \xi + \frac{k_t^2}{6k} \tag{1}$$

Here, θ, $\alpha \cdot r \cdot k^{1/6}$ are the spatial variables, $k = k_0 \cdot (R/R_0)^3$, $\xi = p - p_0 \cdot k^{-\gamma}$. The initial dynamics of bubbles in cluster is rather adequately described by the equation $k_{tt} \simeq -3p/\rho_0 \cdot R_0^2$. This enables to obtain the equation (Helmholtz equation type) for the pressure in cavitating liquid for new spatial variable mentioned above where $\alpha = \sqrt{3k_0}/R_0$ and some assumptions (see Kedrinskii 1976; Hansson et al. 1982). Common solution of system enables to determine the parameters of rarefaction waves, to calculate a cavitation process (see Kedrinskii 1978) as well as to resolve a number of principal questions and, first of all, to form the conception of limit tensile stresses (see Kedrinskii 1976) which may be measured in liquid.

It is known that the rarefaction wave front has a certain steepness Δt_{fr}. The computation of the axisymmetric problem on the cavitation zone development at underwater explosion near the free surface has shown that this fact is of fundamental importance for the problem of ultimate stresses (see Kedrinskii 1976).

One can give some analytical estimation of this effect. Let's consider a tube with real liquid being accelerated vertically downward by an impact (see Hansson et al. 1982). For simplicity the liquid is assumed to occupy a half-space $z > 0$. Under the boundary condition at the tube bottom ($z = 0$): $\partial p/\partial z = -\rho_0 \cdot a(t)$, where $a(t)$ is the tube acceleration, z is the vertical coordinate, the solution of system allows the analytical dependence $p(t)$ to be received for the case $z = 0$ and known $a(t)$. For example, if $a(t) = a_0 \cdot exp(-t/\tau)$, the solution presents the analitical estimation of relaxation time of tensile stresses t_{relax} in cavitating liquid :

$$t_{relax} \simeq 14,3 \cdot (\frac{k_0 R_0^2}{a_0^2})^{1/4} \tag{2}$$

The calculation for $a_0 = 5 \cdot 10^7\ cm/s^2$ (corresponds to $-30\ MPa$ in the rarefaction wave), $k_0 = 10^{-10}$ and $R_0 = 1\mu m$ shows that the relaxation time mentioned (when $p/p_{max} = 1/e$) turned out to be lesser than $0,1\ \mu sec$. To estimate the influence of front steepness on the limit tensile stresses admitted by a cavitating liquid within this statement it will be sufficiently to consider $a(t)$ in the form of linear dependence $a(t) = a_0 \cdot t/\Delta t_{fr}$ where Δt_{fr} is the front steepness. For example, following the conditions of $k = 10^{-11}$ and $R_0 = 0.5\mu m$ for $\Delta t_{fr} = 1\mu sec$ we will obtain $p = -3\ MPa$ instead of $-30\ MPa$ for one-phase model. Calculation of rarefaction wave parameters at underwater explosion (see Kedrinskii 1976) gives the same order of magnitudes for the analogous conditions.

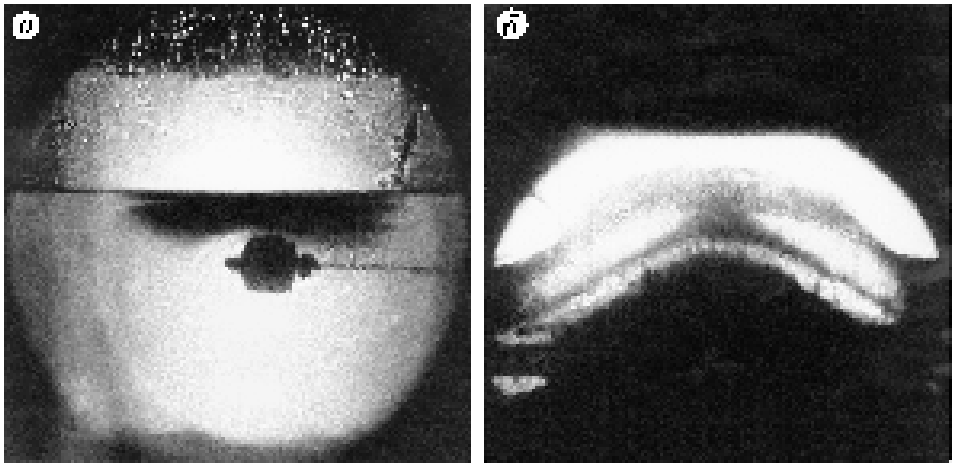

Figure 1: Left: Earlier stage of cavitation zone development at underwater explosion of charge (1gr) near free surface of liquid. Right: later stage - spalling formation.

3 Cavitative fracture of liquid

The later stage of disintegration. As it was noted above, at reasonably intense rarefaction waves the development of bubble cavitation is characterized by unrestricted growth of nuclei of the total theoretically possible spectrum of sizes. Unfortunately, so far there is no complete understanding of significantly nonlinear processes of unbounded growth of bubbles in cavity clusters and their hydrodynamic interaction at formation of dense package with volume concentration of $k_0 \simeq 0.5 - 0.75$ and transition through foam structure to spallation and droplet phase separation.

In the same time the experimental research of the structure of the flow of cavitating liquid at underwater explosion near the free surface has shown that at its destruction in intense rarefaction waves the cavitating spallings (Figure 1) are registered in Kedrinskii (1974). Thus, cavitating liquid manifests both the plastic and brittle properties, that is not characteristic for one-phase liquid medium. It is possible that the requisite conditions for such effect is initially "established" by the wave field.

Disregarding unknown yet details of a transition process from the foam structure into a droplet one, we can assume this process to happen instantaneously as soon as the structure of a cavitation zone achieves the state of dense package of bubbles. Cavitation zone is instantaneously transformed into dense package of elastic spherical liquid droplets, which do not flow together. This model was called "sandy" one. The experimental researches confirmed that such approach is positive.

High-speed photography of the fracture process of both liquid and natural sandy cylindrical shells (Figure 2) at their axial loading has shown the identity of the basic structural peculiarities of two- phase flows : analogous streamer structures characteristic of thin shells and essential stratification of flows to the moment of process completion (small particles take its central parts, while coarse particles are located at the periphery).

The above model with an instantaneous transformation of foam structure into a droplet one was analyzed numerically in Getts and Kedrinskii (1989) in the following statement. Spherical charge of HE with the density ρ_{ch} and radius r_{ch} is surrounded by a shell with outer radius r_{sh} which is a two-phase mixture "liquid particles - air" with a volume fraction of dispersed phase of 0.74 equal to the concentration of dense package of drops. Charge detonation is simulated by an instantaneous explosion at a constant volume and the detonation products have the same density ρ_{ch}. Spherically symmetrical motion of such a two-phase mixture was described by of the well known system of equations for heterogeneous medium mechanics written for each component separately (see, for example, Nigmatulin 1987). The system is closed by the condition of a joint phase deformation (see Getts and Kedrinskii 1989). Numerical calculation were carried out by the method of coarse particles.

The shock wave in disperse phase is initiated as the result of discontinuity decay at the boundary "detonation products - drop shell". When it achieves the outer boundary the shock wave appears in air and

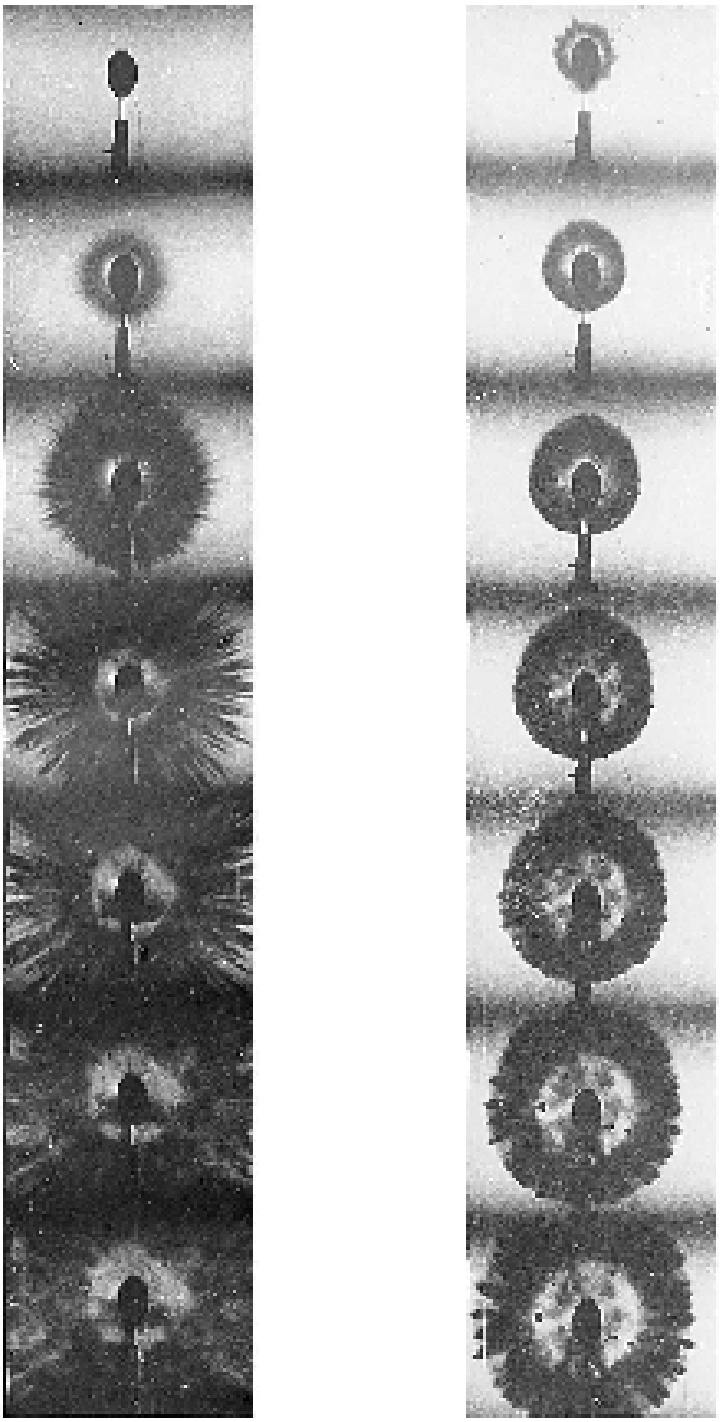

Figure 2: Left: Breaking of sandy shell for $r_{sh}/r_{ch} = 3$. Right: Expansion of sandy shell for $r_{sh}/r_{ch} = 10$.

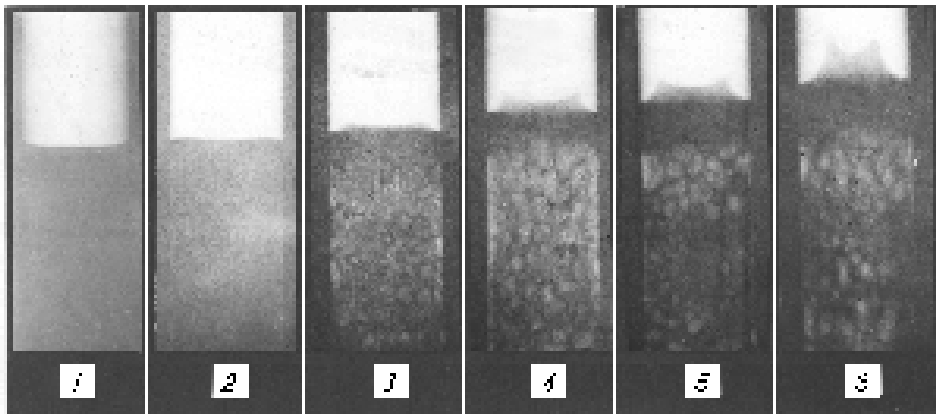

Figure 3: The sequence of x-ray high-speed frames of cavitation zone dynamics as a result of shock wave reflection from free surface (time between frames is 200 μsec.

rarefaction wave propagates into the liquid particles.

Analysis of numerical calculations carried out for explosive of RDX type and water drops at $r_{sh}/r_{ch} = 5$ showed that rarefaction wave along with divergent effects leads to a fast decrease of tensions in the particles, and their density to 20 μsec becomes lower than the bulk one (the particles are separated, the shell became penetrable). The later stage of the process development turned out to be characterized by cumulation of rarefaction wave to the center and rather intense reverse gas flow. This flow decelerates, and later carries away small particles to the center thus determining the mechanism of particle stratification by sizes, observed in experiments with sandy shells. Wave processes in gaseous phase noticeably influence the dynamics of the inner boundary which oscillates with the frequency characteristic of these processes.

Shock tube experiments. As it was mentioned in the field of intense rarefaction waves a cavitation zone development is characterized by practically unlimited inertial expansion of bubbles to the stages where a cavitating liquid is transformed into a structure of foam type and then into a gas-drop system. Based on the experimental studies the following characteristic stages of a process may be noted: a) relaxation of tensile stresses; b) development of dense cavitation clusters (Figure 3); c) formation of a foam structure and d) its disintegration into cavitating fragments and liquid drops.

The intensively developing cavitation zone and the inversion of its state were studied using the shock tube (ST) experiments and pulse x- ray technique. Laser scanering and then computer processing of a density distribution of the X-ray negatives allowed one to obtain easy-to-interpret computer versions of experimental data. Figure 4 (left) presents a liquid sample with cavitation zones in its center and in the vicinity of ST walls. Such approach grants an unique possibility of reconstructing the structure dynamics of the cavitative sample at any cross-section. Computer processing of high-speed frames received with help of pulse x-ray flashes (70 $nsec$ in duration) enables to get and to analyze a sequence of stages of sample structure transformation up to the state closed to the "foam" one.

The model of instantaneous relaxation as well as computer processing of x-ray pictures of cavitation zones allowed one to study the dynamics of its mean density (Figure 4, right) for different values of the deformation rates. Here the following dimensions were used : ρ in gr/cm^3, $\dot{\varepsilon}$ in sec^{-1}, t in $msec$. It's interesting to note that in spite of rather strong inhomogeneity of structure the functions $\rho(t)$ are monotonous ones. The process of pulsed fracture of a liquid as an inversion of its two-phase state with transition from a bubbly- to a gas-droplet- structure was studied using the effect of disintegration of liquid drop as a result of ultra short impact (see Kedrinskii, Besov, Gutnik 1997). It was shown that under pulse loading the initial liquid volume is transformed into the structure of the liquid mesh type in which the decomposition of cells into separate jets and further into drops (Figure 5), scale needle, 1 mm in dia., is in the left frame) makes up an essence of the inversion process.

The calculation of cavitation effects into hemi-spherical drop carried out by Davydov (2000) within the framework of Iordansky-Kogarko-van Wijngaarden model for a distilled water as two-phase medium has shown that an intense cavitation zone is mainly developed in the center part of drop. So, we can say that

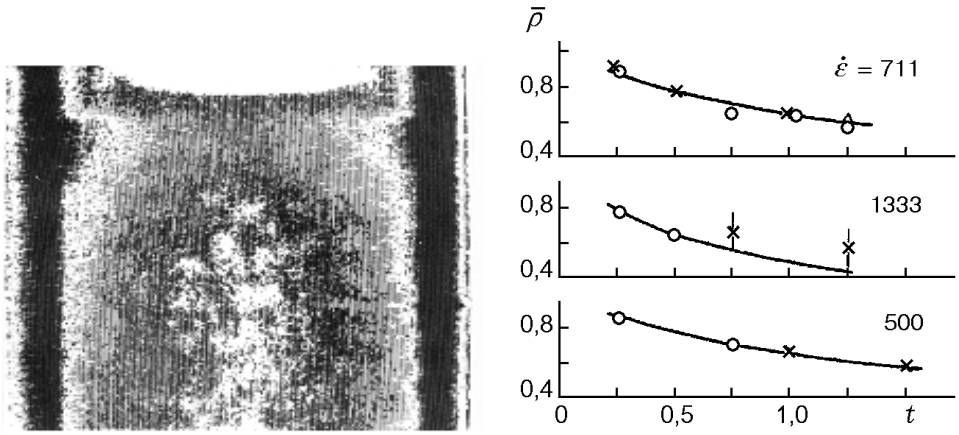

Figure 4: Left:characterisric computer version of x-ray imagination of cavitation zone (black -ST wall and liquid, white - vapour/gas phase). Right: dynamics of mean density of cavitation zone for different values of deformation rates $\dot{\varepsilon}$, sec^{-1}

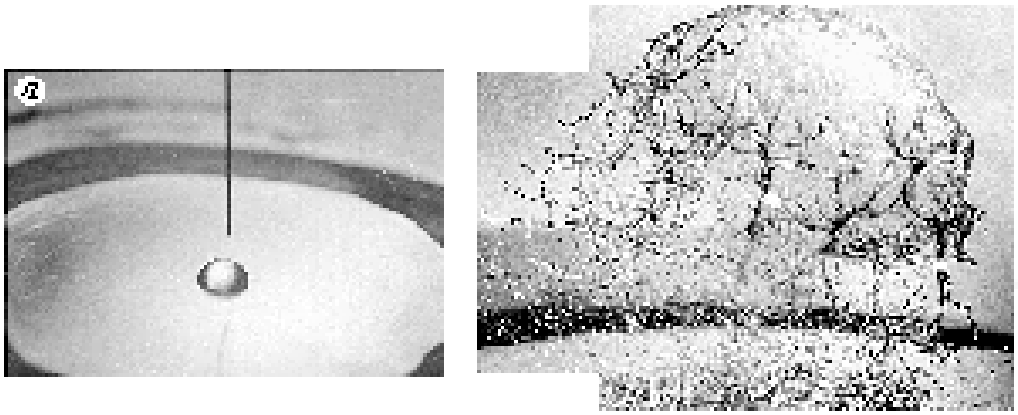

Figure 5: Left:liquid drop (about 1 cm in diameter, $t = 0$) is located on the ST diaphragm. Right: structure of flow at $t \simeq 1.5$ $msec$ after shock wave penetration.

the drop fracture is the result of its "cavitative explosion" from inside (Figure 5, right frame).

4 Conclusions

The given analysis of some essentially nonlinear effects, responsible for the behavior of real liquids under explosive loading, has shown that despite the considerable complexity the construction of adequate physical and mathematical models describing wave processes in cavitating and fracturing liquids as well as dynamics of their state is possible. Considered experiments and proposed techniques allowed to resolve a number of crucial questions concerning the mechanism of the process development of liquid fracture.

From the scope of unsolved problems it is necessary to note the mechanism of "brittle" failure of foam structure and transition "foam - droplets", development of techniques allowing to resolve the total spectrum of nuclei, the questions of stability of their combinations of the type of "gas nuclei - solid particles", the problem of metastable liquid state in "deep" negative phase and the formation kinetics of vapor centers at the front of intense rarefaction wave.

Acknowledgements

This paper is dedicated to the memory of my friend Brad Sturtevant whose interest to the processes of dynamic fracture of liquid was connected with the idea about some adequacy of its mechanisms to processes of explosive volcano eruptions.

References

Carlson, G.A. and Henry, K.W. (1973). *J. Appl. Physics*, **42(5)**.

Davydov, M. (2000) *Proceedings of 6th Workshop on Acoustics of Heterogenious Media*, 25-29 June, Novosibirsk, Russia

Getts, I.G. and Kedrinskii, V.K. (1989) *J. Appl. Mechanics and Tech Physics*, **2**, 120-125

Hammitt, F.G., Koller, A., Ahmed, O., Pyun, J., Yilmaz, E. (1976) *Cavitation, Proc. Int. Conf.*, Mech Eng Publ Ltd London NY, Edinburg, September 3-5

Hansson, I., Kedrinskii, V. and Morch, K. (1982) *J. Physics D: Appl Physics* **15**, 1725-1734

Kedrinskii, V.K. (1974) *Arch. Mech.* **26(3)**, 535-540

Kedrinskii, V.K. (1976) *Acta Astronautica* **3**, 623-632

Kedrinskii, V.K. (1978) *J. Appl. Mechanics and Tech. Physics* **4**, 66-87

Kedrinskii, V.K. (1985) *Ultrasonics Int 85, Proc. Int. Conf., Butterworth Sci Ltd London*, 225-230

Kedrinskii, V.K. (1986) *ICA, Proc. 12th Int. Cong. on Acoust,, Toronto, July 24-31* **14-8**

Kedrinskii, V.K. (1993) *J. Appl. Mechanics and Tech. Physics* **3**, 74-91

Kedrinskii, V.K., Besov, A.S. and Gutnik, I.E. (1997) *DAN*, 352(4), pp.477-479.

Nigmatulin, R.I. (1987) *Moscow, Nauka* **2(6)**

Sirotyuk, M.G. (1968) *Power ultrasonic fields, Nauka, Moscow*, 167-220

Wilson, D.A., Hoyt, J.W., McKune J.W. (1975) *Nature* **253**, 723-5