first-order phase transitions, which include, for example, crystal growth and liquid—vapor transitions. In particular, the investigated mechanism can be used to explain the small sizes of electron—hole droplets formed in semiconductors [3].

The authors are indebted to A. M. Kosevich for calling their attention to the problem.

LITERATURE CITED

1. R. F. Sekerka, "Application of the time dependent theory of interface stability to an isothermal phase transformation," J. Phys. Chem. Solids, 28, No. 6 (1967).
2. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids (2nd edn.), Clarendon Press, Oxford (1959).
3. Yu. A. Bychkov, S. V. Iordanskii, and É. I. Rashba, "Instability and motion of electron—hole droplets," Zh. Eksp. Teor. Fiz., 77, No. 4(10) (1979).
4. L. D. Landau and E. M. Lifshits, Statistical Physics [in Russian], Part 1, Nauka, Moscow (1976).
5. W. W. Mullins and R. F. Sekerka, "Morphological stability of a particle growing by diffusion or heat flow," J. Appl. Phys., 34, 323 (1963).

STRUCTURAL CHARACTERISTICS OF SHOCK WAVES FROM UNDERWATER EXPLOSIONS OF HELICAL CHARGES

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Explosive sound sources have intrigued researchers for many years as a principal component of various kinds of sonar devices designed for the transmission of directional quasicontinuous-wave signals of long duration and large acoustic power. The category of such sources is broad and includes spark-discharge generators [1], condensed liquid [2] and solid high explosives [3-5], explosive gas mixtures [6-8], and the shock-generating effects of collapsing cavities (implosions) [9, 10]. The total energy parameters of the signals from certain explosive sound sources in water have been compared [11], and the spectral characteristics have been studied experimentally [12-16].

Naturally, explosive sources have considerable power, and their transmission is recorded at large distances. These attributes, however, prove inadequate for a broad class of problems in geophysical research, sonic navigation, and scientific investigations of the processes of shock wave propagation in the ocean. Typical problems are the directivity and relatively long duration of the signal, which are not a trivial matter to realize within the framework of explosive sources as predominantly "point" sources. An important problem is the tonal "coloring" of the signal to protect it against reverberation noise. It is not too surprising, therefore, that some of the solutions obtained to date have been based on the familiar notions of classical acoustics in regard to directional transmission from specially distributed sources. The latter represent: an explosive-cord line charge, which ensures shock wave propagation predominantly in a plane perpendicular to its axis [5]; a vertical line array of concentrated charges detonated with a definite frequency [3] and thus generating a prescribed sequence of shock waves, i.e., to a certain extent solving the problem of the duration and "coloring" of the transmitted signal as a result of its directionality. The coherent jetting effect has been utilized in the generation of directional signals by the detonation of a charge in a specially profiled conical liner [4].

There has been definite interest lately in sources in the form of spatial helix configurations of a high-explosive cord (HEC) charge, the transmission from which has a number of specific advantages: directivity both in the vicinity of the axis (typical of an annular source, owing to the high detonation rate) [17] and in the perpendicular plane (certain model of a line source in the case of a long helix); long duration [18]; highly controllable frequency of succession of shock waves for one given total length of the cord charge [19]. The characteristics of the evolution of the wave field from the underwater detonation of such charges are of unquestionable interest. Below, we discuss the fundamental results of their

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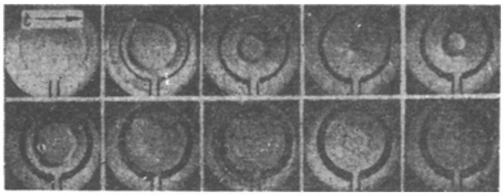

Fig. 1

investigations at the Institute of Hydrodynamics of the Siberian Branch of the Academy of Sciences of the USSR.

Annular Charge. The base of the investigated type of charge is an annular element of HEC detonated at one end. The detonation rate of standard HECs is approximately five times the speed of propagation of sonic compression waves in a liquid, justifying the use of the instantaneous-detonation model in accordance with preliminary estimates. In particular, the explosion of a wire ring can be used for this purpose.

Experiments of this kind have been carried out with the use of a high-voltage apparatus incorporating a capacitor bank, which permits energy to be stored up to several kilojoules and the required part of it to be delivered to a ring of about 5 cm in diameter (Nichrome, d = 0.15 mm). The explosion of such a ring in a liquid can be used to trace the fundamental effects involved in the evolution of the wave field. Typical streak frames of this process are shown in Fig. 1. It is clearly seen that the shock front is the shape of a toroidal surface, and in the vicinity of the ring axis the wave experiences focusing and reflection, which is recorded by the pressure sensor in the form of a compression wave. The streak frames show that the interaction of the reflected wave with the explosion cavity causes a convergent rarefaction wave to propagate inside the ring with the development of bubble cavitation behind the wave front. It is reasonable to assume that with a certain correction for displacement of the wave focusing a similar pattern will emerge in the case of explosion of a ring with a finite detonation rate.

The evolution of the transmitted wave structure in the explosion of an HEC coil has been investigated for charges with diameters of 0.65, 1.65, and 3 mm, a range of ring radii a = 3-30 cm, and distances from the charge 0.5-5 m. Typical streak frames of the process of wave generation and pulsation of the toroidal cavity associated with explosion are shown in Fig. 2a-c. It is seen (Fig. 2a) that three waves are transmitted into space in a sequence that depends on the position of the recording point relative to the detonation zone. In every case the first arrival is a shock wave 1 from the part of the ring nearest the sensor. Then comes wave 2 or 3 (see Fig. 2). Wave 2 is excited behind the front of wave 1 by the terminal part of the ring when the detonation wave front completes a full revolution. This instant corresponds to the beginning of a new revolution of the detonation front in a circular path. Wave 3 is created by the focusing of wave 1 in the interior of the ring. We note that the time interval between the last two streak frames of Fig. 2a is six times the preceding intervals.

The streak photograph of Fig. 2b gives a continuous sweep of the evolution of the wave process in the interior of the ring, the plane of which is parallel to the window. The slit cuts out two diametrically opposite parts of the ring: one far from the detonation point, seen in the upper left part of the photograph as a thin dark line, and the near part, which merges with the lower boundary of the frame. The charge is located relative to the slit in such a way that the focusing point is in the slit, because otherwise it might be possible to record the phase velocity of the convergent waves, creating the impression of a strong increase in the velocity of the wave front. Thus, it is evident from the photograph that a "pure" acoustical process takes place for the particular types and parameters of the high explosive.

Motion-picture frames of the pulsation of the explosion cavity (Fig. 2c, ring diameter 30.5 cm, charge diameter d_0 = 0.65 mm, film speed 1500 frames/sec, detonation rate D = 7.7 km/sec) show that the cavity preserves a toroidal shape, at least during the first pulsation. According to the data of this film, the maximum diameter of the cross section of the cavity with the detonation products at its stopping time is ~$120R_0$. It is seen that, as in the exploding-wire case, the region of the ring is strongly cavitating.

The pressure measurements indicate a strong dependence of the wave structure on the position of the recording point in the near zone of the charge. A transition is observed

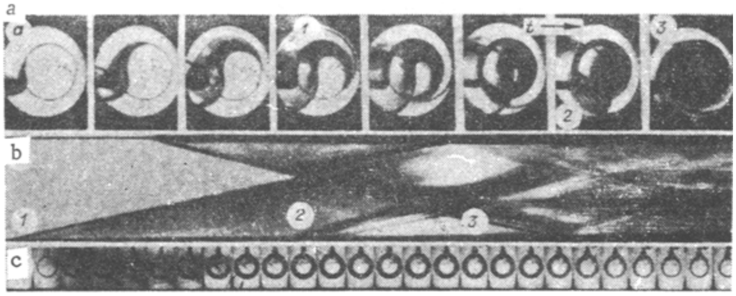

Fig. 2

from sharp separation of the wave into the above-noted three types to a gradual degeneration into one wave. The variation of the parameters of the wave field also differs. Figure 3 shows the variation of the maximum amplitudes of the first wave (relative to the hydrostatic pressure $p_\infty = 10^5$ Pa) as a function of the relative distance along the axis for various radii of the annular charge: 1) a = 30 cm; 2) 20 cm; 3) 10 cm.

All three lines have the same power-law behavior $p_{1,m} = A(\bar{r})^{-1.29}$, where the coefficient A depends on the weight of the charge, i.e., is determined by the radii R_0 of the charge and a of the ring for fixed values of the density ρ_* and type of high explosive. The amplitude of the first wave on the axis of the ring can be described by the approximate relation

$$p_{1,m} \simeq 1.32\cdot 10^6 (R_0/a)^{0.21} (r/R_0)^{-1.29}.$$

It is interesting to note on the basis of this relation that for the same value of r/R_0 the amplitude of wave 1 is greater for a ring with smaller radius a.

The experimental results on the distribution of $p_{1,m}$ in the plane of the ring are plotted in Fig. 4: 1) a = 30 cm; 2) 10 cm. It is found that the pressure at the front of the shock wave from a charge of large radius a diminishes with distance more rapidly (power exponent ~1.65) than for small rings (exponent ~1.15). This result suggests that in the plane of the ring at distances $\bar{r} = r/a \gg 1$ the nature of the pressure distribution is similar to the case of concentrated charges with the same weight as the explosive material of the ring. This conjecture is confirmed experimentally; satisfactory agreement with the data for equivalent concentrated charges is observed in the plane of the ring at distances $\bar{r} \approx 10$ and along the generatrix of the cylindrical surface of radius a at distances $\bar{r} \approx$ 30-40. Measurements of the maximum amplitudes of the second waves show that they can attain very large values and sometimes exceed the amplitude of the first wave, but in the plane of the ring they decay more rapidly with distance than along the axis. This effect can be governed both by wave focusing in the vicinity of the axis and by attenuation due to interaction of the reflected waves with the explosion cavity in the plane of the ring.

Dynamics of a Toroidal Cavity and Transmission. As mentioned above, despite the complexity of the wave structure of the field in the near zone of an annular charge and the finiteness of the detonation rate, various kinds of estimates are obtainable in model settings for the analysis of the process. Thus, making use of the experimental fact that the explosion cavity preserves the shape of a regular torus during the first period, we can investigate its dynamics in the one-dimensional approximation and use the results thereof to analyze the structure of the wave field in the point-source approximation.

The pulsation equation for such a cavity in the setting of an ideal incompressible weightless fluid is readily derived [20]. Accordingly, in the domain $\Omega(t)$ bounded by a closed smooth toroidal surface $\sigma(t)$ we determine the potential $\varphi(\alpha, \beta, \gamma, t)$ such that for $t \geqslant 0$

$$\Omega(t)\colon\ \Delta\varphi = 0,\ \varphi \to 0\ \ (\alpha \to 0,\ \beta \to 0),$$
$$\zeta(\alpha,\ \beta,\ \gamma,\ t) = 0,\ \zeta_t + \nabla\varphi\nabla\zeta = 0,$$
$$\sigma(t)\colon\ \varphi_t + (1/2)(\nabla\varphi)^2 + p/\rho_0 = p_\infty/\rho_0,$$
$$p = p_0 (V_0/V)^{\gamma_0}.$$

At $t = 0$ we have $p = p_0$, $\alpha = \alpha_*$, $\alpha = 0$, and $\sigma(0)$ is the surface of the torus. Here $\zeta(\alpha, \beta, \gamma, t) = 0$ is the equation for the boundary of the domain $\Omega(t)$ in an orthogonal toroidal coordinate system α, β, γ; γ_0 is the adiabatic exponent of the detonation products; V is the volume of gas confined by the surface $\sigma(t)$; and p_∞ is the pressure at infinity.

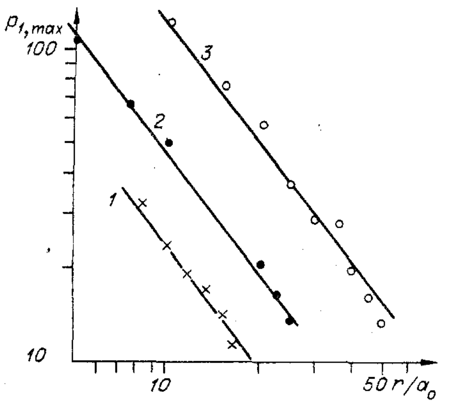

Fig. 3

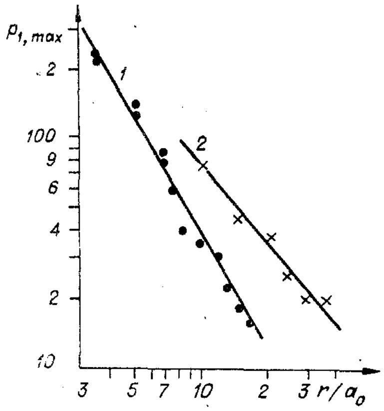

Fig. 4

In the axisymmetrical case the solution for the potential φ has the form

$$\varphi = (2\cosh\alpha - 2\cos\beta)^{1/2}\ [AP_{\nu-1/2}(\cosh\alpha) + BQ_{\nu-1/2}(\cosh\alpha)](C\sin\nu\beta + D\cos\nu\beta).$$

Assuming that σ(t) is always a coordinate surface, we can use the Cauchy—Lagrange integral to derive an expression for the pressure at any point of space and a pulsation equation, which in polar coordinates is written in the form

$$\rho_0\left[(\ln 8a/R)(R\ddot{R} + \dot{R}^2) - \frac{1}{2}\dot{R}^2\right] = p_0(R_0/R)^{2\gamma_0} - p_\infty, \tag{1}$$

where ρ_0 is the density of the liquid, R is the radius of the cross section of the gas cavity, and a is the radius of the ring.

The pulsation equation for a toroidal cavity in a compressible liquid has been obtained in [21] in the acoustical approximation:

$$(\ln 8a/R)[(1-2\pi\dot{R}/c_0\ln 8a/R)\ddot{R}R + (1-\pi\dot{R}/c_0\ln 8a/R)\dot{R}^2] - \dot{R}^2/2 = \omega + \pi R\dot{\omega}/c_0, \tag{2}$$

where $\omega = \int dp/\rho$ and is evaluated at the cavity wall. Calculations show that the principal energy characteristics of the pulsation, namely the expansion time t_* and the maximum cavity radius R_*, agrees satisfactorily with the experimental data for real Hexogen HECs with a detonation rate of 7.7 km/sec.

An analysis of the results of numerical studies carried out over a wide range of values of the ring radius a provides a basis for the derivation of an analytical expression for the maximum value of the relative radius of an expanding toroidal cavity containing detonation products:

$$R_* \simeq 141(1-(2/3)\ln^{-1}8a/R_0).$$

From this result we infer that if a grows without bound, then R_* will tend asymptotically to the value $R_* \approx 141$ obtained for a cylindrical cavity.

The experiments and calculations show that the pulsation period of the toroidal cavity has a singularity in that it grows continuously, albeit slowly, with increasing value of a, and the pulsation period of a cylindrical cavity is not an asymptotic representation for it. An expression for the pulsation period of a toroidal cavity can be obtained by the traditional approach to problems of this kind, namely by analysis of the collapse of a void (vacuous cavity) in an ideal incompressible liquid. Here, of course, the maximum radius R_* of the explosion cavity is an initial value. In Eq. (1) we replace ln $8a/R$ by the value ln $8a/R_0R_*$ on the basis of the well-known fact that during collapse the initial radius of the cavity varies only slightly for the greater part of a half-period, and we neglect the term $\dot{R}^2/2$ in (1). Then, putting $p_0 = 0$, we obtain the equation

$$\rho_0(R\ddot{R} + \dot{R}^2)\ln 8a/R_0R_* \simeq -p_\infty.$$

It enables us to find a solution for R(t) in the explicit form

$$R = \sqrt{R_0^2R_*^2 - p_\infty t^2/\rho_0\ln(8a/R_0R_*)}.$$

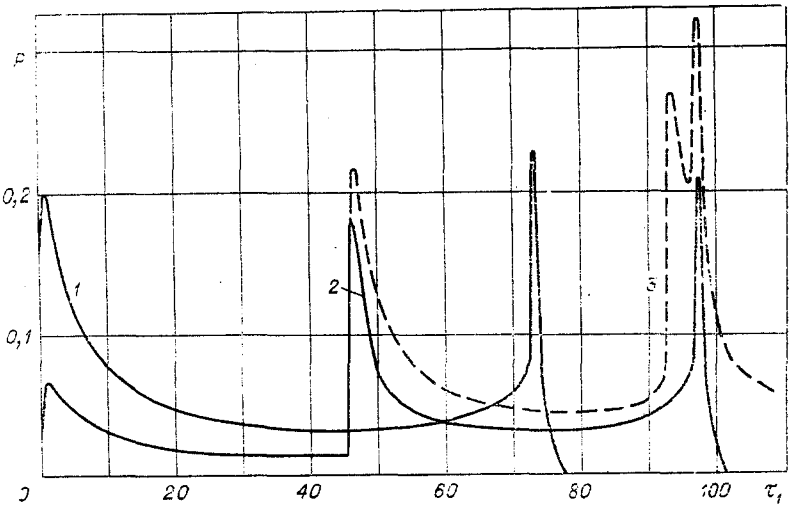

Fig. 5

From this result it is not too difficult to determine the collapse time, and by the symmetry of the process and expansion of the cavity containing the detonation products

$$t_* = R_0 R_* \sqrt{(\rho_0/p_\infty) \ln 8a/R_0 R_*}. \qquad (3)$$

It turns out that the collapse time determined on the basis of (3) coincides, correct to a constant $0.02R_0$, with the experimental results and calculation according to Eq. (2). Consequently, the expression for the first pulsation period of the explosion cavity of an annular charge can finally be obtained in the form

$$T \simeq 2R_0 \sqrt{\rho_0/p_\infty}\,(R_* \sqrt{\ln 8a/R_0 R_*} + 20).$$

We use the model of an annular source to estimate the structure and parameters of the pressure field, assuming that the source is "turned on" instantaneously or is approximated by a set of point sources "turned on" in sequence at the detonation rate. The time variation of the source power at each point of the ring is assumed to be identical and is determined by solving Eq. (2). Numerical estimates of the wave structure are made with regard for the time lags due to the detonation rate D and the acoustic wave velocity c_0. In accordance with the foregoing, the acoustic pressure can be determined as

$$p = \rho \frac{a}{4\pi} \int_0^{2\pi} \frac{\ddot{S}(t-\tau)}{f}\, d\alpha,$$

where $f = \sqrt{z^2 + r^2 + a^2 - 2ar\cos\alpha}$; z, r, α are the coordinates in a cylindrical system; $\tau = (f/c_0 - \alpha a/D)$ is the lag time; the angle α is measured from the line joining the center of the ring with the detonation point; and S is the cross-sectional area of the toroidal cavity. The analysis can be simplified considerably by using the "peak" approximation [22].

Figure 5 gives the results of calculating the wave structure at a point situated at a distance $r = 2a$ in the plane of the ring on the center-to-detonation line. The calculations are carried out for $R_0 = 0.15$ cm, $a = 15$ cm, $D = 7.7$ km/sec. The conditional relative pressure $P = 4\pi p/ap(0)$ is plotted on the vertical, where p(0) is the initial pressure in the detonation products after dissociation. The time τ_1 is taken relative to the constant $\theta_0 = 2.7R_0/c_0$. Curve 1 corresponds to instantaneous detonation, for which only two waves are generated: a shock wave and a compression wave reflected from the ring axis; curve 2 corresponds to a finite detonation rate. Here, in perfect agreement with the experiment, three waves occur. The first and second are shock waves from the initial and terminal parts of the ring, respectively, and the third is a compression wave reflected after focusing. Curve 3 describes the initial transient wave profile for the case of continuous revolution of the detonation front around a ring of radius a.

Wave Structure in the Explosion of Helical Charges. The foregoing experimental and analytical results imply that continuous revolution of the detonation front in a circle must induce the transmission of a periodic sequence of shock waves into the surrounding space. The experimental streak frames in Fig.6a-c prove this fact.

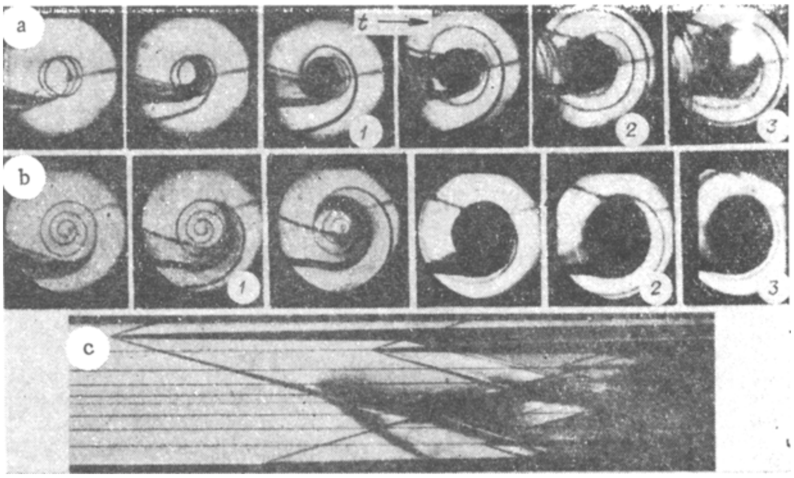

Fig. 6

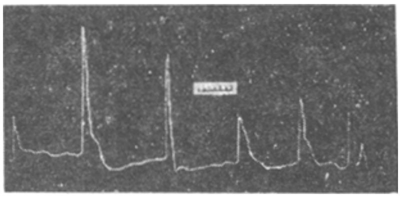

Fig. 7

Figure 6a-b illustrates the evolution of a sequence of three shock waves transmitted into the liquid after an underwater explosion of three-dimensional and plane helical charges. The wave succession period in this packet is exactly equal to the time for the detonation front to traverse the length of one coil. It is fully obvious that, depending on the detonation rate and the linear dimension of the helix (pitch, diameter), two situations can arise at the instant of arrival of the detonation front at the beginning of the next coil. First, the coordinate of the shock front measured from the preceding coil can be much greater than the pitch of the helix. In this event, the explosion of the next coil will take place in a region far behind the shock front, and so for constant parameters of the helix the wave transmission will be determined by a sequence of shock waves of practically identical amplitude for a helix of uniform size. Second, the velocity of the shock front and the axial component of the detonation rate can coincide (Fig. 6a). In this case the pressure oscillograms indicate wave amplification, and the transmission changes its general nature, being no longer a sequence of waves, but a long wave amplitude-modulated at the frequency of revolution of the detonation front around the annular elements of the charge. Of course, these frequencies can differ if the charge contains annular elements with different length dimensions.

Figures 6b-c and 7 clearly illustrate the evolution of the shock wave packet in the underwater explosion of charges of the flat helix type formed from HEC. A continuous sweep (Fig. 6c) shows the interaction of the waves in the interior of a five-turn helix detonated from the outside. It is expected in the explosion of this type of charge that signal transmission will be predominantly in the direction of the symmetry axis or close to it. The pressure oscillogram shown in Fig. 7 was recorded by a sensor situated at a distance of 20 m from a flat helix with an outside radius of 1 m on its geometrical axis. The length of the scale inset shown in Fig. 7 is 400 μsec. Detonation of the charge from the outside produces convergent detonation fronts and imparts a complex nature to the interaction of the transmitted waves, the obvious result of which is periodic amplitude modulation. The latter develops against the background of the naturally expected amplitude modulation associated with the variability of the radii of the conditional annular elements of the flat helix.

The foregoing analysis provides a fairly simple means for estimating the parameters of the signal from the explosion of charges of complex configuration with annular or almost-annular elements. The signal consists of a sequence of shock waves, the amplitudes of which are determined from the data for concentrated charges with the equivalent weight of high-explosive material from each coil. The frequency of succession of the shock waves in the packet is determined by the coil length and the detonation rate, while the total length of the packet is determined by the total length of the HEC in the charge. The latter fact is extremely important insofar as only charges of this type afford a practical means for comparing the duration of the transmitted wave packet with the time for the detonation front to traverse the entire charge.

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LITERATURE CITED

1. H. A. Wright and J. P. Tobey, "Acoustic generator of the spark discharge type," J. Acoust. Soc. Am., 45, No. 1 (1969).
2. N. D. Smith and W. L. Roever, "Liquid seismic explosive and method of using," J. Acoust. Soc. Am., 44, No. 4 (1968).
3. Methods and Device for Echo Ranging, U.S. Pat. No. 3,514,748 (May 26, 1970).
4. W. P. J. Filler, Directional Explosive Echo Ranging Device, U.S. Pat. No. 3,521,725 (July 28, 1970; filed May 18, 1962).
5. R. M. Johnson and C. A. Axelson, Deep Depth Line Charge, U.S. Pat. No. 3,276,366 (October 4, 1966; filed December 28, 1964).
6. V. M. Lyuboshits, "Wave field of a directional explosion," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1 (1968).
7. L. G. Kilmer, "Underwater gas explosion seismic wave generator," J. Acoust. Soc. Am., 45, No. 2 (1969).
8. A. A. Maksakov and N. A. Roi, "Underwater explosion of a detonating gas with a high initial bulk energy density," Akust. Zh., 25, No. 2 (1979).
9. R. S. Brand, "Shock wave generated by cavity collapse," J. Fluid Mech., 2, Part 1 (1965).
10. R. J. Urick, "Implosions as sources of underwater sound," J. Acoust. Soc. Am., 35, No. 12 (1963).
11. M. I. Balashkand, "Comparison of the acoustic efficiency of certain explosive sound sources in water," Dokl. Akad. Nauk SSSR, 194, No. 6 (1970).
12. E. A. Christian, "Source levels for deep underwater explosions," J. Acoust. Soc. Am., 42, No. 4 (1967).
13. A. C. Kibblewhite and R. W. Denham, "Measurements of acoustic energy from underwater explosions," J. Acoust. Soc. Am., 48, No. 1 (Part 2) (1970).
14. R. G. Turner and J. A. Scrimger, "On the depth variation in the energy spectra of underwater explosion charges," J. Acoust. Soc. Am., 48, No. 3 (Part 2) (1970).
15. B. E. Parkis and R. D. Worley, "Measurement of spectrum levels for shallow explosive sources," J. Acoust. Soc. Am., 49, No. 1 (Part 1) (1971).
16. B. M. Buck, "Relative measurements of pulse component source energies of the USN explosive sound signal MU61 detonated at 60 ft," J. Acoust. Soc. Am., 55, No. 1 (1974).
17. M. Seiffert, Method for Generating a Directional Explosion Wave by Means of Underwater Charges, West German Patent No. 2541582 (1977).
18. G. Noddin, "Sonic pulse generator," J. Acoust. Soc. Am., 36, No. 4 (1964).
19. E. V. Lavrent'ev and O. I. Kuzyan, Explosions in the Sea [in Russian], Sudostroenie, Leningrad (1977).
20. V. K. Kedrinskii, "Pulsation of a toroidal gas cavity in a liquid," in: Continuum Dynamics [in Russian], No. 16, Inst. Gidrodin. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1974).
21. V. K. Kedrinskii, "One-dimensional pulsation of a toroidal gas cavity in a compressible liquid," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1977).
22. R. H. Cole, Underwater Explosions, Princeton Univ. Press (1948).