Generation of intense ultrasonic pulses by planar or concave focusing surface exploded by a current or by a laser beam

G. A. Askar'yan, M. G. Korolev, and A. V. Yurkin
Institute of General Physics, Academy of Sciences of the USSR

(Submitted 4 May 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 11, 586–590 (10 June 1990)

The generation and focusing of an intense ultrasonic shock pulse during the electrical or laser-induced explosion of curved surfaces (a metal-coated polyester film, a layer of an absorbing dye, etc.) are described. A pulse with an amplitude of thousands of atmospheres has been produced experimentally in a small spot 6.5 cm away from the emitting surface. Estimates of the nonlinear acoustic self-refraction show that the pressures are close to the limit but might be increased by increasing the focusing angle. Applications of this source of sound are suggested: in research on the nonlinear properties of media, on nonlinear acoustic processes, on the Čerenkov emission of sound from sound, on remote destruction of media, etc.

The generation of intense acoustic shock pulses is a basic problem, whose solution will permit progress in research on the nonlinear properties of substances, in nonlinear acoustics, in the physics of changes in the properties of media (changes in structure or phase, hardening, destruction, etc.), and in other fields.

There are local explosive methods, involving electrical explosions[1,2] or laser-induced explosions,[3,4] for generating strong acoustic shock waves near a zone of a local energy release. This approach is not possible in several fields of research; furthermore, the pulse diverges rapidly with distance, weakens, and loses its shock properties. The focusing of a divergent wave of this sort by lenses or mirrors puts the sound source too far from the object to which the sound is to be applied. As a result, the shock pulses are absorbed as they propagate, and in addition the focal spot broadens, with the further consequence that the shock effect is weakened.

We have studied the emission of sound by exploding surfaces—curved surfaces, which simultaneously generate and focus a sound pulse by virtue of the curvature of the surface,[5,6] and planar surfaces—in direct contact with a lens.

1. Electrical-explosion sound-generating surfaces. As the surface to be exploded, we used a metal-coated film of Lavsan (a polyester) or a surface with an attached layer of metal filings. The layout is shown in Fig. 1. A charging unit charges a capacitance $C = 0.5\ \mu\text{F}$ to a voltage $U = 10$ kV through a resistance $R = 1\ \text{M}\Omega$. A switch (*1*) then discharges the capacitance into the metal coating on the film (*2*), which is below the bottom (*3*) of a water-filled cup (*5*). The bottom of the cup is made of a sheet of cellulose triacetate (the base of a photographic film for technical applications), with a thickness of 0.15 mm. The concave shape of the cup bottom (*3*), produced by hot pressing, matches the concave shape of a subbottom (*7*) made of methyl methacrylate. The film (*2*) is pressed between the bottom and the subbottom. The metal coating makes good contact with electrodes (*4*). It was found that thin layers of a liquid (water, alcohol, or oil) in the gaps between the film, the bottom, and the subbottom substantially increase the strength of the sound pulse. The point of importance here is the shock contact, not acoustic matching, since the layer thicknesses are far smaller than the effective wavelength of the sound.[1)] The focus of the mirror is at a distance of 6.5 cm. Open-shutter photography with dense filters revealed that the energy release occurred over the entire surface of the mirror.

The sound was detected by ceramic piezoelectric transducers cemented to or pressed against acoustically matched brass rods. We used two transducers: I, with an area of 2 mm^2, a thickness of 1.25 mm, and a sensitivity $K = 0.05$ V/atm, intended for measuring high pressures; and II, with an area of 3 mm^2, a thickness of 0.5 mm, and a sensitivity $K = 0.001$ V/atm. To avoid damaging or dislodging transducer II at high amplitudes ($> 10^3$ atm), we used a brass cover plate to press it against the rod. Transducer I, which was calibrated in a quasistatic procedure in a circuit with a source follower with a very large input resistance, prevented charge from draining from the

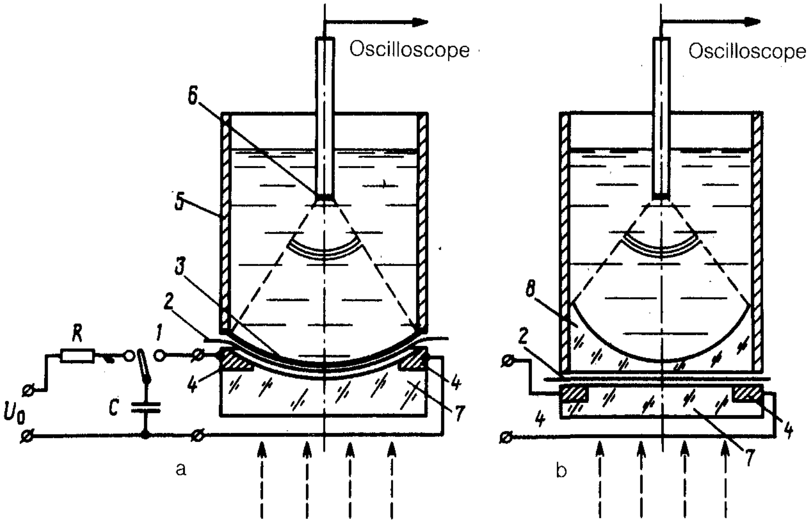

FIG. 1. Layout for generating shock pulses through the electrical explosion of a surface. a: Concave surface in an active-mirror regime. b: Plane surface to be exploded beside a lens. *1*—Terminal for charging the capacitor and for discharging it into the surface to be exploded; *2*—metal-coated Lavsan film (or layer of metal particles); *3*—bottom (hot-stamped from a sheet of cellulose triacetate) pressed or cemented to vessel *5*, which holds water; *4*—electrodes which supply current to the surface to be exploded; *6*—calibrated piezoelectric transducer; *7*—methyl methacrylate subbottom; *8*—polystyrene acoustic lens which focuses sound in the water at a distance of 6.8 cm. Thin layers of a liquid (water, alcohol, or capacitor oil) between film *2*, bottom *3*, and subbottom *7* greatly improve the efficiency of the sound generation. In the case of a laser-induced explosion, not only a metal-coated film but also a layer of an absorbing dye between bottom *3* and subbottom *7* was used. In some of the experiments, the bottom was made of a thin titanium foil coated on the outside with an absorbing dye, on top of which the subbottom was replaced by several layers of Lavsan film, cement, a gel, etc.

transducer during the application of the calibration pressure. Transducer II was also calibrated against the readings of transducers I and II during the application of the same sound pulse. The quasistatic linearity of the readings of these transducers was tested in the working pressure range.

Figures 2a and 2b show oscilloscope traces of the pulses from transducer II at the focus (b) and in the case of a plane wave (a), at a distance approximately equal to the focal length in case *b*. At a plane-wave amplitude $p_0 \approx 300$ atm, we achieved an amplification by a factor of ≈ 4 at the focus; the pressure reached 1100 atm. The pulse had a steep front, with a rise time less than several tenths of a microsecond. The length of the pulse was 2–4 μs in the focused wave or 1 μs in the plane wave. As we will show below, the modest amplification factors are a consequence of the large initial amplitudes in the plane wave.

The curve in Fig. 3 shows the measurements of the focal region by transducer II. This curve reveals the width of the spot at half the maximum pressure to be $\Delta \approx 10$ mm, while the diameter of the initial spot is $d \approx 50$ mm (and we have a ratio $p_{s\mathrm{foc}}/P_{so} \approx d/\Delta \approx 5$).

We studied the destruction of various materials at the focus.

Figure 4 shows the application of a pulse to a medium at the focus of a plate 1 mm thick. In frame *a*, the medium is glass on the surface of a liquid; in frame *b*, the medium is the same as in frame *a*, with a methyl methacrylate plate; and in frame *c*, the medium is a rosin plate (the focus is in the liquid volume). We see that the effect is very local (the damage zone is 3 mm in size). We observed the destruction of rocks,

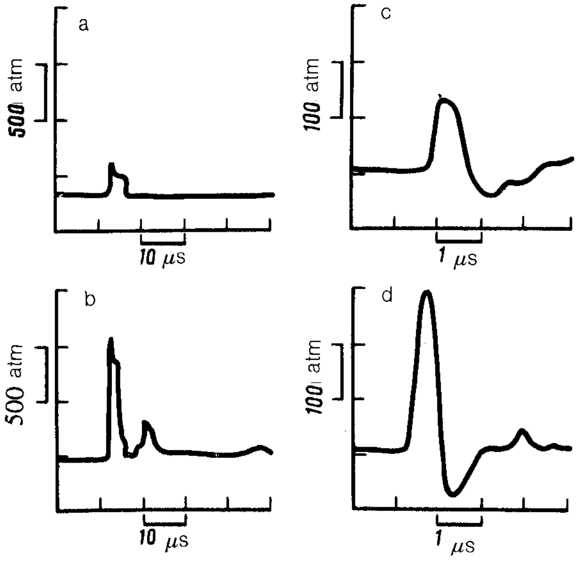

FIG. 2. Oscilloscope traces of the detection of pulses from (*a*,*b*) electrical and (*c*,*d*) laser-induced explosions of a metal-coated film. *a*—Pulses in a plane wave without focusing; *b*—pulses at the focus in the case of an electrical explosion; *c*,*d*—the same, for a laser-induced explosion.

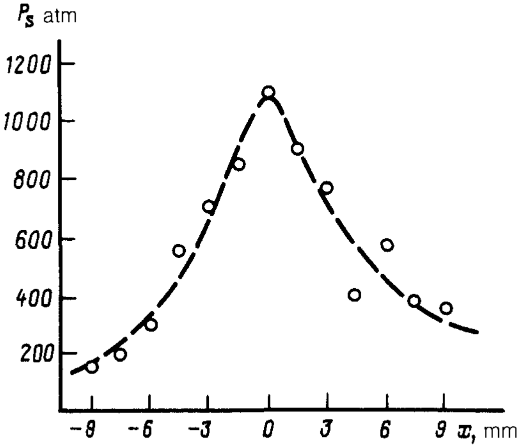

FIG. 3. The pressure distribution in the focal plane in the case of an electrical explosion revealed a severalfold increase in the pressure in the focus, with a spot width < 1 cm.

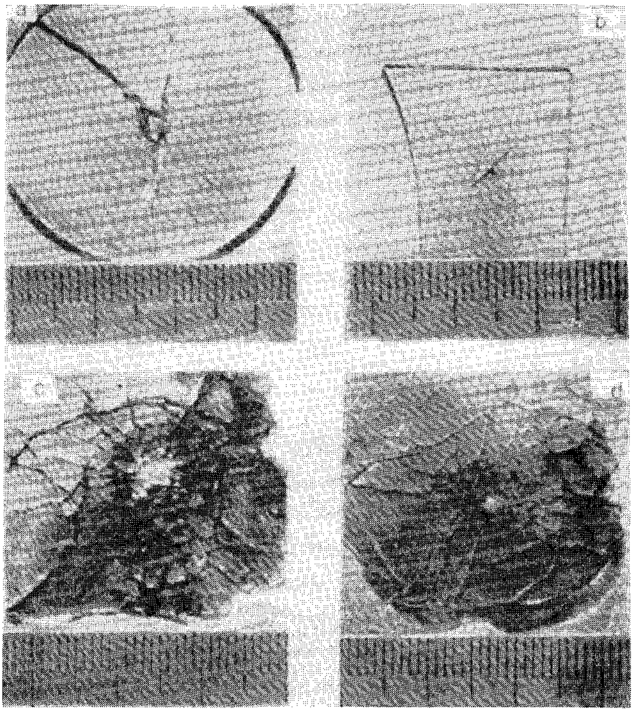

FIG. 4. Effect of a focused pulse from the electrical explosion of a film on various media (plates 1.5 mm thick). *a*—Punctured and cracked glass; *b*—the same, for polymethyl methacrylate; *c*—punctured layer of rosin on tracing-paper substrate; *d*—the same, as a result of a pulse from a laser explosion, for comparison. The effect of the electrical explosion is seen to be stronger and more concentrated. In all cases, the focal length is $F = 6.5$ cm.

pieces of brick, ceramic, etc.

The electrical-explosion sources are distinguished by their high efficiency. The pulses can be repeated frequently (in fact, it is possible to carry out the charging with several metal-coated films, to which the exploding voltages are applied in succession).

The effect of the rapid nonlinearity on the focusing of individual intense pulses was estimated.

An approximate nonaberrational equation for the effective radius of the sound beam can be found from the refraction equation $\theta_z' = -(1/n)n_r' \approx (1/n)(\Delta n/a)$, where n is an analog of the refractive index $n = c_{so}/c_s$. For a fast nonlinearity, the sound velocity is $c_s = c_{s0}\epsilon u$, where ϵ is a nonlinearity parameter $[(\epsilon = \frac{1}{2}(\Gamma + 1)$, where Γ is the adiabatic constant, $\Gamma \approx 7$–8 for water], and $u \approx p/\rho c_s$ is the velocity of the medium in the wave. We find $n = 1/(1 + Ap)$ and $\Delta n = n - 1 = Ap/(1 + Ap)$. We thus have $(1/n)(\Delta n/a) \approx Ap/a$, where $A = \epsilon/\rho c_s^2$. The nonlinear-refraction equation takes the form $a_{zz}'' = Ap/a \approx Ap_0a_0/a^2$, since we have $p = p_0a_0/a$, and $\theta = a_z'$. Multiplying both sides by a_z' and integrating, we find the relationship $\theta_0^2 - \theta^2 = 2Ap_0a_0[(1/a)] - (1/a_0)]$. At the focal waist we have $\theta = 0$ and thus $\theta_0^2 = 2A(p_f - p_0)$; i.e., the amplitude at the focus depends strongly on the focusing angle $\theta_0 \approx a/F$. Knowing p_f, we can also estimate the dimensions of the waist: $a_f \approx a_0p_0/p_f$. These relations incorporate neither the absorption nor the diffraction of the sound, since these factors can be ignored under the conditions of interest here.

In our case we have $\theta_0 \approx 0.3$, $A \approx 2 \times 10^{-10}$ *abs*, and thus $p_f - p_0 \approx 0.3 \times 10^3$ atm or $p_f \approx 0.5 \times 10^3$ atm, in quite good agreement with experiment. Incorporating diffraction, we find $\theta_0^2 \approx 2A(p_f - p_0) + (\lambda^2/4a_0^2)[(p_f^2/p_0^2) - 1]$, where $\lambda \approx 0.1$ cm is the effective wavelength of the pulse.

2. Laser-explosion sound-generating surfaces. An attempt was made to use a laser to explode metal-coated and absorbing films in order to generate intense sound pulses. In contrast with Refs. 7 and 8, where an absorbing liquid near a curved surface was heated by a laser beam, we developed a radiation in the form of a cover plate. Various versions of this cover plate could be used for a variety of purposes.

Figure 1 shows the layout; the dashed arrows show the unfocused laser light. Common to the first series of laser experiments were the methyl methacrylate subbottom (*7*) and the vessel bottom (*3*), which was made of a thin, concave layer on a cellulose triacetate base.

Between them was a metal-coated Lavsan film or a layer of a water color (ink), applied with a brush or poured on and held in place with a subbottom clamp.

In a second series of laser experiments, bottom *3* was replaced by a stamped titanium foil sphere coated on the outside with a layer of water color or a nitro dye, and subbottom *7* was replaced by transparent layers which increased the recoil: several layers of a Lavsan film not coated with metal, a layer of cement, or a viscous medium (a gel or jelly), deposited on the bottom on top of an absorber (L. D. Klebanov participated in this series of experiments).

Cover plates with a coating of a water color and a dye turned out to be more convenient than cover plates with a film, since they withstood many pulses.

As the laser light we used unfocused Q-switched pulses from a neodymium laser based on a GOS-1001 device, with Q switching by means of a self-brightening LiF shutter. The energy of each pulse was on the order of 10 J, and the pulse length was 40–50 ns. We detected sound pulses with an amplitude of 300–500 atm in a focus 1–2 mm in size at a focal length of 3.4 cm. We observed localized damage to the plates of rosin, the ceramic transducers, etc. We tested focal lengths of 6.5 and 3 cm.

At small focal lengths, the evidence of the damage was more localized.

The laser version requires a far larger power supply and far more energy because of the low efficiency ($<10^{-3}$) of the laser in Q-switched operation.

The pressures measured at the focus were close to the limit for our convergence angles. Although the pressure at the focus could be increased by increasing the convergence angle, the remoteness of the strong effect—the main point of all this—would be sacrificed. The focal length $F \approx 6.5$ cm was chosen because of cases of practical interest for the use of this method.[10]

What sort of physical studies could be carried out with the help of these intense pulses?

The primary field of research is that of the instantaneous nonlinearities associated with the sudden movement of the medium in a sound pulse (even a single pulse!). Here there is a substantial difference from the nonlinearities associated with the build-up of heating during linear or nonlinear absorption of a long train of pulses. This field of fast nonlinearities has not received much study. From the evolution of the pulse we can find the effective adiabatic indices of a liquid and its values for different pressure ranges.

There are also some important and unique opportunities for studying the behavior of compact, single ultrastrong pulses in liquids and for observing Čerenkov waves from them (we recall that propagation velocity of these waves is higher than the velocity of sound in the medium).

There are broad opportunities for using these intense pulses for a sterile initiation of reactions, for remote control of structure formation (or, on the contrary, for destroying media[10]), etc.

Such pulses might find widespread use in biology and in medicine, in applications ranging from small-scale remote effects to the crushing of foreign objects.[10]

[1] K. A. Naugol'nykh and N. A. Roĭ, *Electric Discharges in Water*, Nauka, Moscow, 1971.

[2] L. A. Yutkin, *Electrohydraulic Effect*, Mashgiz, Moscow, 1955.

[3] G. A. Askar'yan *et al.*, Zh. Eksp. Teor. Fiz. **44**, 2180 (1963) [Sov. Phys. JETP **17**, 1463 (1963)].

[4] C. E. Bell and J. A. Landt, Appl. Phys. Lett. **10**, 46 (1967).

[5] G. A. Askar'yan, Zh. Tekh. Fiz. **29**, 277 (1959) [Sov. Phys. Tech. Phys. **4**, 243 (1959)].

[6] A. I. Bozhkov and F. V. Bunkin, Akust. Zh. **24**, 932 (1978) [Sov. Phys. Acoust. **24**, 527 (1978)].

[7] A. M. Galstyan *et al.*, Akust. Zh. **25**, 926 (1979) [Sov. Phys. Acoust. **25**, 521 (1979)].

[8] G. A. Askar'yan and L. D. Klebanov, Kvant. Elektron. (Moscow) **15**, 2167 (1988) [Sov. J. Quantum Electron. **18**, 1359 (1988)].

[9] L. K. Zarembo and V. A. Krasil'nikov, *Introduction to Nonlinear Acoustics*, Nauka, Moscow, 1966.

[10] R. A. Riehle, Jr. (editor), *Principles of Extrocorporeal Shock Wave Lithotripsy*, Churchill Livingstone, New York, 1987.

Translated by D. Parsons