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ACOUSTIC CERENKOV RADIATION AND ITS UTILIZATION IN HOLOGRAPHY METHODS TO STUDY MOVING MEDIA

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An interference interpretation is presented for acoustic Cerenkov radiation and we consider the possibility of its utilization as a basis of holography methods to study moving media.

In [1, 2] we find an examination of the possibility of using the sound scattering effect to find the average velocity and distribution of velocities for combustion products on the basis of the cross-sectional area of a combustion chamber. A new phenomenon has been studied rather recently, and namely, the acoustic Cerenkov radiation [3, 4] and some of its aspects of application, in particular, the utilization of this effect in solving problems analogous to those presented in [2].

In the present paper we put forward an "interference" interpretation of acoustic Cerenkov radiation and we examine a new approach to the solution of problems (analogous to those mentioned above), based on the utilization of the Cerenkov radiation and the methods of dynamic holography [5-9]. These questions are fundamental, both from the standpoint of validating the possibilities of using this new approach to the solution of numerous applied problems, as well as in connection with the fact that the solution that we will present later on is subsequently necessary for a more detailed and penetrating investigation into the process of holography, in the processing and deciphering of the results, etc.

The methods and means presently at hand to determine the parameters of moving media (in particular, products of combustion) frequently are of inadequate accuracy, and the resulting information, as a rule, is both insufficient and fails to provide a complete picture of the phenomena being studied. The latter, in turn, is one of the reasons why the determination of the values for the parameters of the medium are determined with unsatisfactory accuracy.

In our opinion, an extremely promising approach, in terms of the completeness of information and its accuracy, involves the methods of dynamic holography in combination with acoustic Cerenkov radiation. In particular, this approach may prove to be useful in studying nonsteady and fast-moving processes, since the information about the medium may be developed virtually instantaneously and it will exhibit four-dimensional characteristics (the three coordinates and time). Moreover, we have the possibility of contact-free (i.e., performed on the outside surface of the wall, or of the combustion chamber) probing in which the probe region is situated at a considerable distance from the point of "egress" for the combustion products from the combustion chamber, with the information being transmitted to the outside at a controlled Cerenkov angle.

The use of acoustic Cerenkov radiation expands the possibilities of dynamic holography, i.e., new channels for the transmission of information are created (with the Cerenkov angle), and the hologram itself will differ from the familiar features encountered in the supersonic (or in faster-than-light with electromagnetic radiation) motion of an interference grid. Moreover, the information on the medium (the object) is obtained virtually instantaneously,

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while at the same time it is possible to store this information for long periods of time in the form of holograms, using this data whenever necessary.

Let us take note of the fact that the range of questions which can be solved on the basis of this new approach is rather broad and not limited to the problems cited above. Here we can include, for example, the problem of determining the parameters of a heat-carrying coolant and the regime of its motion in the hydraulic systems of atomic and thermal electric power stations, problems in metrology, the study of the thermal boundary layer, etc.

Acoustic Cerenkov radiation is analogous in form to the appearance of Vavilov–Cerenkov radiation in electrodynamics, with the latter, however, generated by supersonic interference waves. In the "interference" interpretation discussed later on (in contrast to that dealt with in [3, 4], according to which the Cerenkov radiation arises on satisfaction of the conditions of spatial synchronism) the possibility of exciting Cerenkov waves is determined primarily by "aerodynamic" forces. The essence of this phenomenon is to be found in the following. Two bundles of acoustic waves exhibiting similar filling frequencies ω_1, ω_2 are directed at each other. In the area at which these bundles intersect a four-dimensional interference grid is formed out of the forced waves with the combined frequency, moving at a speed greater than the phase speed of sound. As a result, cones of Cerenkov waves are formed outside of this region of intersection. The direction and velocity of motion for these "sources" (interference grids) of Cerenkov waves are determined exclusively by the kinematics of wave imposition within the bundles, in connection with which, in principle, the velocity of the "sources" is not bounded from above.

Under the conditions prevailing within the combustion chamber the medium is found to be in a nonequilibrium state. When we take this fact into consideration, we can derive the wave equation for the problem of Cerenkov radiation in a coordinate system ξor moving at a velocity V_0 (equal to the velocity of the "sources") relative to the laboratory system ($\xi = z - V_0 t$):

$$\bar{\gamma}^2 \frac{\partial^2 \rho'}{\partial \xi^2} + \frac{1}{r}\frac{\partial \rho'}{\partial r} + \frac{\partial^2 \rho'}{\partial r^2} - \frac{m c_0^2}{\tau c_\infty^2} \Delta \int\limits_{-\infty}^{t} \rho'(t') \exp\left(-\frac{t-t'}{\tau}\right) dt' = \tag{1}$$

$$= 2\frac{\rho_0}{c_\infty} A_{10} A_{20} \frac{\Omega^2}{c_\infty^2}\left[1 - \frac{\gamma - 1}{2}\frac{V_0}{c_\infty}\right] \exp\left\{-\frac{r^2}{a^2} + i\left[\omega_c t - \left(k_c + \frac{r^2}{a^2}N\right)z\right]\right\}.$$

We use the conditions at infinity as the boundary condition for this problem. The right-hand side in Eq. (1) describes the supersonic "sources," makes provision for the diffraction divergence of the bundles, as well as for the parabolic distribution of the acoustic parametric values for the cross-sectional area of the bundle. The solution of this equation in the form of an angular spectrum is presented in the form

$$F = \frac{2R \exp(-\mu^2 a^2/16)}{\left[k_c^2 - 2k_\xi (k_c - k_\xi) + \mu^2/\bar{\gamma}^2\right]}\left[\exp(-\bar{m}\xi) - \left(1 - i\frac{N}{2}\xi\right)\exp(-ik_c\xi)\right]. \tag{2}$$

From (2) we can derive an expression for the amplitude of the acoustic Cerenkov radiation:

$$A(r,\xi) = R\left\{\frac{\xi}{[\xi^2 - |\bar{\gamma}|^2 r^2]^{3/2}} \frac{J_0(r|\bar{\gamma}|k_\xi)}{k_0^2}\left[1 - \frac{a^2}{16}\left\{\frac{15|\bar{\gamma}|^2\xi^2}{[\xi^2 - |\bar{\gamma}|^2 r^2]^2} - \right.\right.\right. \tag{3}$$

$$\left.\left. - \frac{9|\bar{\gamma}|^2}{[\xi^2 - |\bar{\gamma}|^2 r^2]} - k_\xi^2\right\}\right] - \frac{\pi}{2}\left\{\left[a_0\left(1 - \frac{a^2 k_\xi^2 |\bar{\gamma}|^2}{16}\right) + b_0\frac{N}{2}\xi\right] + i\left[b_0\left(1 - \frac{a^2 k_\xi^2 |\bar{\gamma}|^2}{16}\right) - ia_0\frac{N}{2}\xi\right]\right\}\right\};$$

$$a_0 = N_0(r|\bar{\gamma}|k_0)\cos\bar{k}_c\xi + J_0(r|\bar{\gamma}|k_0)\sin\bar{k}_c\xi,$$
$$b_0 = J_0(r|\bar{\gamma}|k_0)\cos\bar{k}_c\xi - N_0(r|\bar{\gamma}|k_0)\sin\bar{k}_c\xi \tag{4}$$

($J_0(r|\bar{\gamma}|k_0)$, $N_0(r|\bar{\gamma}|k_0)$ are Bessel and Neumann functions).

In Eq. (3) the factor N represents the diffraction divergence of the supersonic bundle at the total frequency. The reduction in the amplitude in the radial direction is determined from the expression $(N\xi/2)(a_0 + b_0)$. The second term in (3) describes the "blurring" of the surface of the Cerenkov cone, a consequence of the parabolic distribution of the acoustic oscillatory velocities over the cross-sectional area of the bundles.

Asymptotic estimates demonstrate that the surface of the Cerenkov cone retains its complex configuration, while the amplitude is reduced in accordance with the law of a diverging cylindrical wave and directly proportional to the amplitudes of the primary waves, with the velocities V_0 dependent on the selection of the frequencies ω_1 and ω_2, and additionally, the amplitude increases as the wavelength of the total frequency increases and it diminishes as the diameter of the interference bundle increases (more precisely, it depends on the relationship between these parameters). The reduction in the amplitude of the Cerenkov waves due to the diffraction divergence of the bundles is proportional to the distance from the point of origin for the primary radiation waves to the region at which the "sources" are formed. From (3) we also have the possibility of controlling the Cerenkov radiation by varying the parameters which define the radiation.

This solution describes Cerenkov waves generated by bundles of unlimited extent, when the excitation (if we keep to the concept of the "interference" interpretation) is actually engendered by that region of the interference bundle near the surface. However, the intensity of the Cerenkov radiation in this case, as shown by calculation, is exceedingly small, and the excitation itself is of little effect. Based on an analysis of the results from the "interference" interpretation we can draw the conclusion that the most effective excitation of Cerenkov waves will occur in the interaction of short pulses. Indeed, in this case the level of Cerenkov radiation is governed by the magnitude of the "frontal" resistance, which is considerably greater for the pulse than for the region of a bundle of unlimited extent near the surface. In order to solve this problem we will assume that the density $\rho = f(w, s)$ and the entropy $S = \text{const}$. If we use the familiar thermodynamic relationships for the potential of velocities we will obtain the following equation:

$$\frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{\partial^2\varphi}{\partial r^2} - \bar{\gamma}^2\frac{\partial^2\varphi}{\partial\xi^2} = 0 \tag{5}$$

and the condition at the "surface" of the pulse (it is assumed that the bundles of the acoustic waves are well collimated)

$$\partial\varphi/\partial r = V_0\partial R/\partial\xi. \tag{6}$$

On the basis of (5) and (6), the expression for the force of the "frontal" resistance of the conic pulse, propagating along the ξ axis, has the form

$$F_\xi = \rho_0 V_0 \beta^4 \int_0^l \left(2\pi \sqrt{\xi^2 - |\bar{\gamma}|^2 r^2} - \operatorname{arch}\frac{\xi}{\bar{\gamma} r}\right)\exp(-ik_c\xi)\,d\xi. \tag{7}$$

In terms of order of magnitude the solution of Eq. (7) is the following:

$$F_\xi \sim \frac{\rho_0 V_0 S^2}{l_0^2} = \pi\rho_0 V_0 \frac{a^2}{16 l_0}. \tag{8}$$

Using expression (8) to solve the problem of the field generated by a supersonic conic pulse, we come to

$$\bar{\gamma}^2\frac{\partial^2\rho'}{\partial\xi^2} + \frac{1}{r}\frac{\partial\rho'}{\partial r} + \frac{\partial^2\rho'}{\partial r^2} = \frac{\rho_0 V_0^2}{c_\infty^2}\frac{\bar{S}}{l_p V_p}\exp(-r^2/a^2)\operatorname{div}[\delta(\xi)]. \tag{9}$$

The solution for Eq. (9), found through application of the Fourier–Hankel transform, is written as follows:

$$\rho'(r, \xi) = L\int_0^\infty\int_{-\infty}^\infty \frac{\eta\exp(-a^2\mu^2/4)\,J_0(\mu r)\,\mu d\mu d\eta}{\mu^2 + |\bar{\gamma}|^2\eta^2}. \tag{10}$$

Let us examine the case in which $V_0 > c_\infty$ (in this case a singularity arises in (10) and to eliminate nonsinglevaluedness we introduce the Dirac δ function [10, 11]).

Limiting ourselves to two terms in the expansion of the exponential series in (10), after integration over μ, we obtain

$$\rho'(r, \xi) = L|\bar{\gamma}|^2 K_0(i|\bar{\gamma}|\eta r)[1 - \eta^2 a^2/4] \tag{11}$$

($K_0(i|\bar{\gamma}|\eta r)$ is the MacDonald function). If the target wave with a phase perturbation $\varphi_1(x, y, z)$, acquired, for example, as a result of the interaction with the material in the combustion chamber, and the reference wave are described by the expressions

$$\begin{aligned} \rho_1'(x, y, z) &= A_{10} \exp \{i[k_1 r + \varphi_1(x, y, z) - \omega_1 t]\}, \\ \rho_2'(x, y, z) &= A_{20} \exp \{i[k_2 r - \omega_2 t]\}, \end{aligned} \tag{12}$$

the solution of the Cerenkov radiation problem subsequent to transform (11) with respect to η and with consideration of (12) assumes the form

$$\rho'(r, \xi) = \frac{\pi L |\bar{\gamma}|^2}{2} \frac{\xi}{[\xi^2 - |\bar{\gamma}|^2 r^2]^{3/2}} \left\{1 - \frac{3}{2} \frac{a^2}{[\xi^2 - |\bar{\gamma}|^2 r^2]}\right\} \{\exp[-i(k\xi - \varphi(r, \xi))] + \exp(ik\xi)\}.$$

The phase change in the target [object] wave thus modulates the Cerenkov wave cones, i.e., the phase information regarding the object (the material in the combustion chamber, in this case) changes over to the front of the Cerenkov waves.

Figure 1 shows the basic diagram for probing that is based on acoustic Cerenkov radiation and dynamic holography in combustion chamber 1. The tests are conducted in a contact-free fashion (i.e., from the outside surface of the chamber through its wall) and this is possible not only to the right of the cross section B_1B_2, but in the cross section A_1A_2 as well, i.e., at sufficiently great distances from the outlet from the chamber. The points A_1A_2 (as well as B_1B_2) serve as radiators of acoustic supersonic filling pulses, exhibiting frequencies of ω_1, ω_2, Rec_1, Rec_2 are the acoustic receiver converters, Amp identifies the signal amplifier, and L denotes the laser. The duration of the pulses is equal to the time required for the signal to cover the distance A_1A_2. In the case of axial symmetry for the chamber, when its diameter is not large, it is convenient to use annular (tubular) radiators, also mounted on the outside through the acoustic transition layer. In this case, the monitoring probe operation encompasses the entire cross-sectional area of the flow [3]. If the wave frequency of radiator A_1 is larger than $A_2(\omega_1 > \omega_2)$, the "sources" of the Cerenkov waves move in the direction from A_2 to A_1, and the wave front O_1O_2 of the Cerenkov wave is propagated at an angle θ to the trajectory of the "sources" in the direction $\mathbf{k}_C$. Control of the angle θ (by varying the values of ω_1, ω_2) can be achieved because the Cerenkov waves from the "sources" move along the trajectory of A_2O_1 and thus leave the chamber entirely, with the consequent information regarding the medium in the lower part of the probe section, and can be recorded on hologram H_1. Similar information about the upper portion of the cross section is recorded on hologram H_2, provided that the frequency values for the second pulses are substituted one for the other. It is also possible to have simultaneous probing in two planes (A_1A_2; A_3A_4) situated in the immediate vicinity of each other; if the radiators at points A_1, A_4 and A_2, A_3 exhibit frequencies of ω_1 and ω_2, respectively (see Fig. 1).

For an illuminated visualization of the object (of the medium in the chamber) we can use a multichannel ultrasonic light modulator M [12]. In this case, the Cerenkov wave carrying information about the medium enters receiver $Rec_{1,2}$ (one that is continuous or in the form of a grid of sound receivers). The acoustic pulses generated by the Cerenkov wave are converted into electrical voltage and act on the diffraction light modulator M. As a result, the light wave will be modulated by the acoustic Cerenkov wave of the object and this modulation will be reflected in the hologram H_2 (the points A_1, A_2, A_1'', A_2''). However, in our

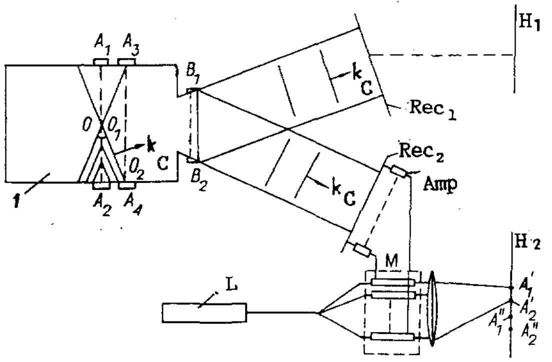

Fig. 1

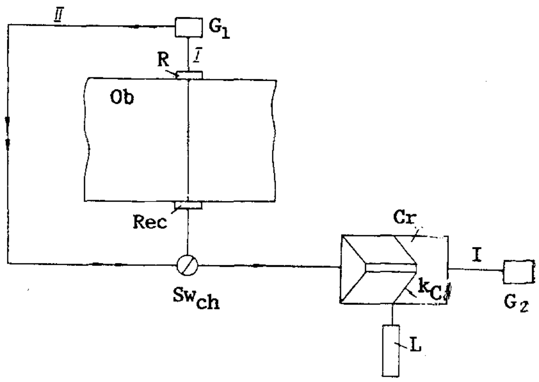

Fig. 2

opinion, more promising for such investigations are the methods of dynamic echoholography [5], whose significant difference lies in the fact that the object and reference signals are separated over time, and the signals from the primary or stimulated light echos function in the role of the probing signals. In multilevel systems it is possible to transmit the energy contained in the fronts of the acoustic Cerenkov waves to the wave fronts of the optical signals (or vice versa). With pulsed acoustic probing short pulses of acoustic Cerenkov radiation will emanate out of the probing area at the Cerenkov angle. If the first two pulses forming the hologram (for example, outside of the combustion chamber), are pulses of acoustic Cerenkov waves (one of which comes from the object), and a third pulse is a laser pulse with a plane wave front, then the stimulated echo signal will be one that is optical, with a wave front reproducing the front of the Cerenkov wave. It thus becomes possible to visualize the information of the medium recorded in the fronts of the acoustic Cerenkov radiation. The reproduced field of echoradiation has the form

$$E \sim \mathrm{Re}\left\{\sum_i \varepsilon^* \exp(-ik_{1i}R_0)\right\},$$

i.e., the field at the point R_0, generated by the echowave, contains a pseudoscopic image of the object. The amplitude depends on the values of the relaxation parameters, the velocity of motion for the medium being studied, and other factors, forming the hologram, as well as on the properties of the material in which this recording is being accomplished.

Let us examine one of the possible schemes of resonance recording and reading the information contained in the wave front of the acoustic Cerenkov wave and in the visualization produced by the optical echosignal (Fig. 2). Acoustic pulses with plane wave fronts of carrier frequencies ω_1, ω_2, developed by generators G_1 and G_2 are fed over independent acoustic channels to the opposite faces of the crystal Cr, for example $MgO:Fe^{2+}$. The generator G_1, for example, may have two channels (I, II), one of which passes through the medium (Sw_{ch} is a channel switching device, R and Rec denote the radiator and receiver of the acoustic signals, and Ob is the object). Initially, the first pulses from generators G_1 and G_2 (or the pulses from one of these) simultaneously and in resonance impinge on the crystal. The second pulses are sent through the time interval τ smaller than the minimum of all of the times of irreversible relaxations, with the signal from generator G_1 passing through channel II, through the segment containing the medium. After passage through this segment, the signal picks up the information about the distribution of particle frequencies, their concentration, and with respect to other characteristics of the medium. The interaction within the crystal between the wave from the object and the reference wave generated by generator G_1, with a plane front, under certain conditions [4] leads to the excitation of an acoustic Cerenkov wave. As a result of the action of the first and second pulses of the acoustic waves on the crystal under conditions suitable for the existence of a phase memory a Cerenkov interferogram is formed within the crystal, and information about the medium under investigation is recorded here. This information can be read out by means of an optical pulse with a carrier frequency and a resonance transition between the lowest and excited energy levels. The crystal radiates information about the medium in the combustion chamber, contained in the acoustic Cerenkov wave, in the form of a signal of a stimulated light echo, with the additional information associated with the supersonic motion of the "sources" transmitted at the Cerenkov angle. Similar setups can be used in metering flow rates, in level gages, etc.

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TOMOGRAPHIC DETERMINATION OF PARTICLE DISTRIBUTION BY VELOCITIES

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1. Measurement of the fluorescence spectrum of a rarefied medium (of a gas or plasma) allows us to determine one of the most important characteristics of the medium, and namely, the distribution function (DF) of the particles by velocities. In the traditional (single-aspect) formulation, in order to determine the DF the $q(\nu, \mathbf{n})$ spectrum of radiation propagating in the direction $\mathbf{n}$ is recorded. In this case the function $q(\nu, \mathbf{n})$ is associated with the function $f(v, \mathbf{n})$ for the distribution of the particles along the projections of the velocities in the direction of $\mathbf{n}$ by the following equation [1, 2]:

$$\int_{-\infty}^{\infty} K\left(\frac{\nu_0}{c}(v - v')\right) f(v', \mathbf{n})\, dv' = q\left(\nu_0 \frac{v}{c}, \mathbf{n}\right). \qquad (1.1)$$

Here $K(\nu)$ is the kernel by means of which we take into consideration the effects of the non-Doppler broadening mechanisms and the equipment function of the spectral instrumentation; $\nu = \nu_0 v/c$; ν_0 is the frequency characterizing the position of the center of the radiation lines; c is the speed of light.

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