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Electrothermal sound receivers

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An analysis of the physical processes occurring during the emission of sound waves by electrothermal sound sources (thermophones) showed that a thermophone is a reversible physical system. This made it possible to determine the conditions under which the convertion of an acoustic signal into an alternating electric current can be carried out on the thermophone active element and, hence, the system will respond to an external acoustic field.

Keywords: acoustic signal, active element, metal film, electric current, electrothermal receiver.

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At present, sound sources, namely, thermophones, are exploited in research work. The thermophone emits sound waves due to the thermoacoustic effect [1]. Performance capability of thermophones has been confirmed by, e. g. experimental investigation of acoustic parameters of film thermophones [2,3]. This paper shows that the layered structure of the film thermophone may be used to create an electrothermal sound receiver in which the acoustic signal interacting with the system active element is converted into an electric signal.

Let us consider the structure of the layered system which is used in electrothermal sound receivers to convert acoustic signals into alternating electric current (see the figure). The direct current I_0 flowing through the active element (AE) *2* provides the system preheating and stabilization of its thermodynamic operating mode. Due to heat exchange with the environment and carrier plate *3*, the AE temperature gets stabilized and becomes equal to T_S. Thereat, relation $T_S > T_0$ is always valid, where T_0 is the static temperature of the system in its initial state.

On the device AE *2* there occurs conversion of the acoustic signal to alternating electric current. AEs of the devices are typically fabricated in the form of electrically conductive thin films. The film thicknesses range from 20 nm to $1-5\,\mu$m. The carrier plate *3* of the device ensures mechanical strength of the system as well as removal of stationary heat fluxes arising in the device AE during flowing of direct electric current I_0 through it. In fabricating the plates, dielectric materials are used. The plate thickness is chosen so as to ensure mechanical strength of the device and equals $1-3$ mm.

During the acoustic waves propagation in a heat-conductive medium *1*, the medium substance temperature varies periodically [1]. To describe the wave interacting with the AE top surface, let us use the acoustic additive to the medium temperature. The acoustic field in space *1* arises due to interaction between the incident acoustic wave T' and reflected one T'_{12}. It is assumed that on the AE surface inequation $kr_0 \gg 1$ is fulfilled, where $k = \omega c$ is the wave number, c is the sound speed in gas, ω is the frequency of wave T', r_0 is the radius of the circular-shaped sound receiver whose area is covered by a grid of electric conductors forming AE.

To analyze the results of the acoustic field interaction with the surface of solid body whose substance is characterized by finite values of thermophysical parameters, the method developed in [4,5] was used. This analysis allowed establishing the following facts.

Interaction of the acoustic field with the AE surface (plane $x = 0$) results in formation of two nonuniform heat waves. Heat wave $\mathbf{k}_{T1}$ propagates in gas with forming an acoustic boundary layer (ABL) in the half-space *1* (see the figure). Heat wave $\mathbf{k}_{T2}$ exists in the AE *2* material and induces ABL inside it. The consequence of the heat wave $\mathbf{k}_{T2}$ emergence in a thin layer of electrically conductive substance *2* is a variable-temperature field affecting the conductor electric resistance. Equation of the heat wave $\mathbf{k}_{T2}$ propagation has the following form:

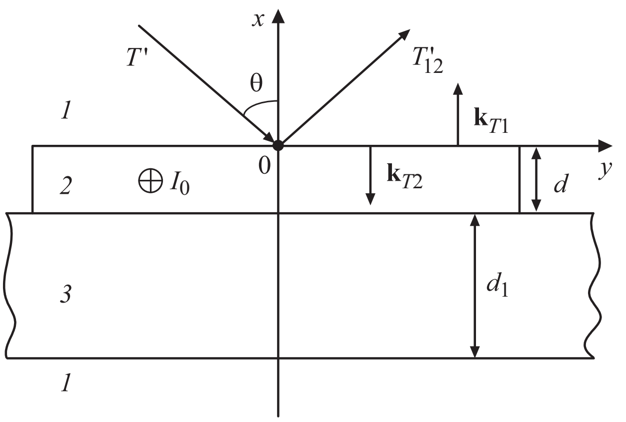
$$T'_{T2} = T'_{m2} e^{-\frac{x}{\delta_{T2}}} \cos\left(\frac{x}{\delta_{T2}} - k_{y2} y\right), \tag{1}$$

where $\delta_{T2} = \sqrt{2a_2/\omega}$ is the thickness of ABL in the substance; a_2 is the substance thermal conductivity coefficient; $k_{y2} = k_2 \cos\theta_2$; $k_2 = \omega/c_2$ is the wave number; θ_2 is the wave refraction angle.

It follows from papers [4,5] that in the sound frequency range, at the wave T' incident angles θ of 0 to 75°, the heat wave (1) amplitude is independent of the incident angle and is

$$T'_{m2} = 2T'_m = \frac{\gamma - 1}{\beta_V} \frac{2u_m}{c}, \tag{2}$$

where u_m is the amplitude of the wave oscillation speed; $\gamma = C_P/C_V$ is the Poisson coefficient; C_P and C_V are the gas specific heat capacities at constant pressure and volume, respectively; β_V is the thermal expansion coefficient of the



Structural pattern of the layered system on which the signal conversion takes place. *1* — gas, *2* — electrically conductive layer, *3* — carrier plate. I_0 is the reference direct current, d is the AE thickness, d_1 is the carrier plate thickness, $d_1 \gg d$.

medium; T'_m is the amplitude of the acoustic additive to the medium temperature in incident wave T'.

In the initial state, there is no acoustic field in the gaseous medium *1* (see the figure). Application of potential difference u_0 to the AE *2* connectors gives rise to direct current I_0 in it. The AE substance gets heated to stationary temperature T_S. The magnitude of circuit current I_0 is determined by the active resistance

$$R_S = R_{20}\left[1 + \alpha_{\rho 2}(T_S - T_0)\right], \tag{3}$$

where R_{20} is the conductor electric resistance at 20°C; $\alpha_{\rho 2}$ is the temperature resistance coefficient of the AE substance.

If the acoustic field is generated in the gas, the total medium temperature in the AE bulk will be $T_S + 2T'_{m1}\sin\omega t$. As a result of interaction between the variable temperature field and AE substance, an alternating active resistance emerges in the electrical circuit:

$$R_{ae} = R_{am}\sin\omega t, \tag{4}$$

where $R_{am} = 2R_S\alpha_{\rho 2}T'_{m2} = 4R_S\alpha_{\rho 2}T'_m$ is the amplitude of the alternating active resistance.

Application of dc potential difference u_0 to the AE connectors leads to that the emergence of time-variable acoustic resistance (4) generates in the electrical circuit an alternating potential difference

$$u(t) = u_{am}\sin\omega t, \tag{5}$$

where $u_{am} = 4u_0\alpha_{\rho 2}T'_m$ is the signal amplitude.

Further, signal $u(t)$ is picked up from AE by using a special electrical circuit and fed to the electric-signal processing system. The electric signal amplitude linearly depends on the amplitude of sound wave T' incident on the AE surface.

The frequency range of the acoustic signal electrothermal converter is defined by the thickness of the AE electrically conductive layer. The AE thickness d is being selected so as to ensure uniform heating of the layer through its thickness and satisfies inequation

$$d \leqslant 0.50\pi\delta_{T2}. \tag{6}$$

Find from condition (6) the limiting frequency at which it remains valid, namely,

$$f_d = 0.785a_2/d^2. \tag{7}$$

Thus, the operating frequency range of the acoustic signal electrothermal converter corresponds to frequencies $f \leqslant f_d$.

Using the definition of the microphone sensitivity, obtain a relation for calculating the sensitivity of the acoustic signal electrothermal converter:

$$\xi_P = 4u_0\alpha_{\rho 2}\frac{\gamma - 1}{\beta_V\rho c^2}, \tag{8}$$

where ρ is the gas density.

Formula (8) shows that the converter sensitivity linearly depends on the dc potential difference u_0 applied to the AE connectors and on the temperature resistance coefficient of the substance the AE is made from.

Response rate of the developed device is defined by attenuation and rise of the temperature amplitude of the oscillation process induced in the AE substance. Time coefficient of the heat wave (1) attenuation is independent of physical parameters of the medium where it has been induced and is defined as $\beta_{T2} = \omega$. Thus, the device possesses the oscillation process time constant

$$\tau_{T2} = 1/\beta_{T2} = 0.159T \ [\text{s}], \tag{9}$$

where T is the oscillation period of sound wave T'.

Formula (9) implies that the heat wave in AE gets induced and disappears practically in real time following variations in the acoustic field parameters.

Let us perform numerical estimation of the device parameters. For comparison, consider two versions of the device under the assumption that their AEs have identical geometric shapes and dimensions ensuring the AE thickness $d = 3.3\,\mu$m. To create the electrically conductive layers, iron and titanium are used. Both AEs are applied on a flat thermostated surface where condition $T_S = 293$ K is fulfilled. The acoustic field gets induced in air at the static pressure of 1.0 atm. Using the above-presented formulae, obtain the following results: $f_d = 1.5$ MHz, $\xi_P = 190\,\mu$V/Pa for iron; $f_d = 0.6$ MHz, $\xi_P = 102\,\mu$V/Pa for titanium.

The calculation results allow making the following conclusions. The device will enable conversion of the acoustic field into alternating electric current in the sound and low-ultrasound frequency ranges. Sensitivity of all the converters is sufficient for subsequent processing of the electric signals; however, signal pre-amplification is necessary. The metal for fabricating the converter AE is to be chosen based on the production process capabilities and required economic efficiency.

Conflict of interests

The authors declare that they have no conflict of interests.

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