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Acoustoelectric transducer based on electrokinetic phenomenon flow potential

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A mathematical model of an acoustoelectric transducer based on the use of the electrokinetic phenomenon of the flow potential is proposed. It is shown theoretically that the flow potential increases in proportion to the strength of the constant electric pumping field, which is confirmed experimentally. The described converter has variable sensitivity. Rather large values of the sensitivity of an electrokinetic microphone have been obtained experimentally. The results of the work can be used in the design of acoustoelectric transducers.

Keywords: Acoustoelectric conversion, Electrokinetic phenomena, Current potential, Flow potential hydrodynamics, Energy pumping. Electrokinetic microphone sensitivity.

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Earlier in the studies [1–3], an electroacoustic conversion based on the electrokinetic phenomenon (EPh) electroosmosis was considered. The main difference from the previously existing similar conversions (see, for example, the work of [4]) is the use of the pumping mode of the energy of acoustic vibrations due to the energy additionally applied to the porous medium of a constant electric field.

In this paper, an acoustoelectric conversion based on the EPh flow potential is considered also in the presence of a pumping process. Without pumping mode, this problem is considered in [4, § 3]. In the presence of pumping in the process of acoustoelectric conversion, both EPh are used: both the electroosmosis and the flow potential. For the first time, theoretically, considering the pumping process, this issue was partially considered in [5] and other works of the authors. The theoretical aspects outlined in these papers are briefly presented here, as well as new results on the topic under consideration.

The acoustoelectric conversion is based on the EPh flow potential — the phenomenon of the occurrence of a potential difference at the ends of a capillary (porous body) during the flow of liquid in it. The main role in this is played by the electric double layer formed at the interface of phases and its polarization. For simplification, this phenomenon is considered in a cylindrical capillary, in which electrokinetic processes are similar to processes in a conventional porous structure with not very burdensome assumptions [6, § 2.2]. The capillary axis is further assumed to be oriented along the axis $0z$.

The process of formation of a potential difference $\Delta\varphi$ at the ends of a capillary filled with liquid when an acoustic field is applied is described in detail, for example, in [6, § 2.5]. The expression relating the magnitude of the flow potential at the ends of the capillary $\Delta\varphi$ (i.e., the potential difference) with the magnitude of the pressure drop on them Δp has the form [6, p. 10; 7, p. 516]:

$$\Delta\varphi = -\varepsilon\varepsilon_0\tilde{\xi}\Delta p/\eta\sigma. \tag{1}$$

Here σ — specific conductivity of the liquid, ε, ε_0— respectively, the dielectric constant of the liquid and the electrical constant, $\tilde{\xi}$ — zeta potential, η — dynamic viscosity liquids. Relation (1) shows that the flow potential does not depend on the cross-sectional area of the capillary, but is given only by the magnitude of the pressure drop [7, p. 516]. When switching to a real connected-dispersed system, complications arise, however, the described regularity (1) remains valid in this case [8, p. 184].

In (1) values of $\Delta\varphi$ and Δp are independent of time and represent the differences of the corresponding values at the ends of the capillary. In the case of their dependence on time and the z coordinate on the capillary axis in [5], an equation is obtained for the functions $\varphi(z, t)$ and $p(z, t)$

$$-\rho_e\partial\varphi/\partial z = (\rho_e\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)\partial p/\partial z, \tag{2}$$

where ρ_e — the volume density of the electric charge in the electrolyte. Let $\mathbf{E} = -\nabla\varphi$ — the value of the electric voltage vector corresponding to the flow potential. From (2), taking into account the assumption $\mathbf{E} = (0, 0, E)$ for harmonic processes $\mathbf{E}(z)\exp(-i\omega t)$ and $p\exp(-i\omega t)$, the expression is valid [5]:

$$\mathbf{F} = \rho_e\mathbf{E}(z) = (\rho_e\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)\partial p/\partial z, \tag{3}$$

that is, in the case of a flow potential, a volumetric force $\mathbf{F}$ (3) acting on the liquid arises.

The mechanism of the pumping process by analyzing the Navier–Stokes equation in relation to the acoustoelectric conversion, when a constant electric field $\mathbf{E}_0$ and an external acoustic field with pressure p_a are simultaneously applied to the ends of a capillary filled with liquid, is given in [5]. After separating the linear (acoustic) part from the original nonlinear Navier–Stokes equation, the following linear equation with respect to acoustic fields is obtained ($\mathbf{v}$, p)

$$\rho_0\big(\partial\mathbf{v}/\partial t + (\mathbf{v}_0\cdot\nabla)\mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v}_0\big) = -\nabla p + \eta\Delta\mathbf{v} + (\xi + \eta/3)\nabla\nabla\cdot\mathbf{v} + \mathbf{F}. \quad (4)$$

Here $\mathbf{v}_0$ — the velocity field caused by a stationary electric field $\mathbf{E}_0$; ρ_0 — stationary liquid density; ξ — volumetric viscosity; $\mathbf{F}$ — volumetric force, which is defined in (3). To the equation of motion (4) a standard linearized continuity equation for a compressible fluid should be added $\frac{\partial\rho}{\partial t} + \rho_0\nabla\cdot\mathbf{v} = 0$.

To simplify equation (4), we assume a small thickness of the double layer at the interface between the liquid and the inner surface of the capillary, which is determined by the inequality $\kappa a >> 1$ ($\kappa = 1/\lambda$; λ — thickness of the double layer; a — capillary radius). In this case, the velocity of the electroosmotic fluid motion in almost the entire capillary section is equal to the osmotic velocity of Helmholtz–Smolukhovsky U_{eo} [6, p. 10]:

$$U_{eo} = E_0\varepsilon\varepsilon_0\tilde{\xi}/\eta = \text{const}. \quad (5)$$

Thus, we have in the cylindrical coordinate system $\mathbf{v}_0 = (0, 0, U_{eo})$, which leads to the expression $(\mathbf{v}_0\cdot\nabla)\mathbf{v} = U_{eo}\partial\mathbf{v}/\partial z$ [9, p. 68, 83] or finally taking into account (5)

$$(\mathbf{v}\cdot\nabla)\mathbf{v} = U_{eo}\partial\mathbf{v}/\partial z = E_0(\varepsilon\varepsilon_0/\eta)\tilde{\xi}\partial\mathbf{v}/\partial z.$$

Let us rewrite (4) taking into account the last equality, as well as the obvious equality $\nabla\mathbf{v}_0 \equiv 0$.

$$\rho_0\partial\mathbf{v}/\partial t = -\nabla p + \eta\Delta\mathbf{v} + \big(\xi + \eta/3\big)\nabla\nabla\cdot\mathbf{v} - \rho_0 U_{eo}\partial\mathbf{v}/\partial z. \quad (6)$$

Assuming the process to be potential $\mathbf{v} = \nabla\Phi$, similarly to [3], we reduce (6) to a scalar form (taking into account the possibility of switching operators here $\partial/\partial z\nabla = \nabla\partial/\partial z$ [9, p. 84])

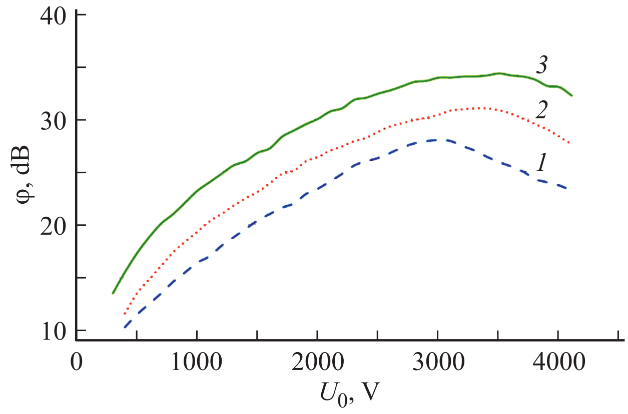
$$\rho_0\partial\Phi/\partial t = -p + (\xi + 4\eta/3)\Delta\Phi - \rho_0 U_{eo}\partial\Phi/\partial z. \quad (7)$$

In the harmonic case with the time factor $\exp(-i\omega t)$, keeping the same notation for the amplitudes, for the amplitude of the potential Φ from (7) we obtain the Helmholtz equation

$$\Delta\Phi + k^2\Phi = (k^2/i\omega)U_{eo}\partial\Phi/\partial z, \quad (8)$$

$k^2 = (\omega^2/c^2)\rho_0/\big((\rho_0 - i\omega/c^2)(\xi + 4\eta/3)\big)$ — the square of the corresponding wave number.

Equation (8) — inhomogeneous Helmholtz equation with respect to the amplitude of the potential Φ velocity $\mathbf{v}$. It follows from (8) that with an increase in the magnitude of the velocity U_{eo}, the magnitude of the amplitude Φ should increase, and hence the magnitude of the amplitudes $\mathbf{v}$ and p, since there are dependencies $\mathbf{v} = \nabla\Phi$, $p = (\rho_0 c^2/i\omega)\Delta\Phi$. The analysis in [5] shows that with an increase in the velocity of the electroosmotic flow, the magnitude of the flow potential also increases.



Dependences of the flow potential φ in the receiver on the value of the pumping voltage U_0 at the pressure values of the acoustic field $p_{ai} = 85$ (*1*), 90 (*2*) and 95 (*3*).

Full-scale experiments were conducted to test the theory. As a receiver, a matrix located in an air environment was used — a pack of A4 office paper with a thickness of 2.5 mm, placed between two perforated aluminum plates-electrodes. An electric field $\mathbf{E}_0$ was applied to the electrodes of the matrix. The alternating voltage formed in the matrix under the influence of an external sound field was removed from the electrodes. In the first experiment, the effect of pumping on the magnitude of the flow potential was studied. At a frequency of $f = 2$ kHz, the speaker at a fixed distance from the matrix alternately emitted acoustic pressure p_a of three different levels fixed at the aperture of the matrix $p_{ai} = 85, 90, 95$ dB ($i = 1, 2, 3$) relative to level $20\,\mu$Pa. At each fixed pressure, the dependence of the flow potential φ_i on the potential U_0 of the electric field E_0 was measured: $\varphi_i = f(p_{ai}, U_0)$ ($|E_0| = |U_0|/d$), where d — the thickness of the paper layer). The measurement results are presented in the figure The curves *1*, *2* and *3* correspond to the pressure at the aperture of 85, 90 and 95dB, respectively. The value of the flow potential φ depending on U_0 was measured in relative units. The figure shows the similar behavior of the curves in all three cases. First, the flow potential increases proportionally to U_0, then a saturation zone is observed, and finally, with the growth of U_0, a decrease in the flow potential φ occurs. This is explained by the appearance of a turbulent regime of fluid motion at certain values of U_0 in the porous structure of the matrix. The figure also shows that the sensitivity of the transducer at a fixed acoustic field p_{ai} is a variable value and depends on U_0. In the second experiment, the sensitivity values of the transducer were calculated. The sound with a frequency

Dependence of sensitivity on pumping U_0 at sound pressure $p = 0.893$ Pa

Pumping U_0, V	Flow potential φ, mV	Sensitivity mV/Pa
0	1189	1330
132	1603	1795
397	2018	2259
529	2540	2841
661	2851	3191
1322	4027	4507

of 1 kHz had a pressure level on the plane of the transducer 93 dB. Sensitivity was measured at different pumping levels. The measurement results are summarized in a table.

As a result of the conducted research, the physical and mathematical models of the receiver functioning based on the use of the flow potential are proposed. It is theoretically shown and experimentally confirmed that the flow potential increases in proportion to the magnitude of the electric field of the pump. Experimentally revealed the presence of saturation in this process, due to the nonlinearity of the process and the emergence of a regime of turbulent fluid motion in the body of the transducer.

The sensitivity of the electrokinetic microphone was significantly higher than that of the most sensitive carbon and condenser microphones: 200–400 and 10 mV/Pa respectively [10, p. 152].

The results of the work can be used in the theory and practice of designing reversible electroacoustic and acoustoelectric transducers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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