HEAT TRANSFER IN ELECTRODYNAMIC TRANSDUCERS

V. I. Kordonskii, S. A. Demchuk, V. A. Kuz'min, and É. A. Zal'tsgendler

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Heat transfer in the voice coil of a dynamic loudspeaker is analyzed in detail with allowance for its design features. The theoretical estimates of the investigated process are corroborated experimentally; it is shown, in particular, that the nature and intensity of heat transfer in the voice coil depends significantly on its position in the magnetic gap of the dynamic speaker. The most favorable regime in this case is conductive heat transfer, when the coil is situated exactly in the gap. Conclusions are drawn as to possible ways of increasing the rate of heat transfer in the voice coil of a dynamic speaker.

Present-day high-performance acoustical systems must be capable of reproducing high peak sound pressure levels in the transmission of musical programs covering a broad frequency range. The main part of this power is dissipated as heat in the voice coil of the electrodynamic transducer (dynamic loudspeaker) [1]. The temperature of the voice coil can attain 120°C or more in this case. Such heating is destructive to the coil (the coil overheats, the coil forms warps and suffers damage, and the adhesive scorches and melts). Moreover, excessive overheating increases the resistance of the coil, thereby creating a mismatch with the filter circuits and causing the electroacoustical characteristics to deteriorate.

A detailed analysis of heat transfer in a voice coil with allowance for all its design features has not been published to date. The results of such an analysis would certainly provide a basis for the development of new approaches to the design of high-power acoustical systems.

Thus, the heat-transfer conditions in the voice coil largely determine the service attributes and technical characteristics of a dynamic speaker. An effective means for increasing the rate of heat transfer in the voice coil in a number of cases is to fill the magnetic gap with a magnetized fluid medium [2, 3]. This approach is best suited to high-frequency systems with insignificant movement of the coil along the height of the gap. On the other hand, this approach is inapplicable for a broad category of speakers, primarily because the moving system experiences large displacements. Moreover, speakers differ in the position of the voice coil, which is an important design attribute from the standpoint of heat transfer: The entire coil can be situated in the gap (see Fig. 1a), part of the coil can project downward from the gap (Fig. 1b), or all or part of the coil can project above the gap (Fig. 1c).

The gap region of the magnetic circuit of a dynamic speaker can be partitioned into four zones (Fig. 1a): the air layer 1; the cardboard form 2; the coil winding 3; the air layer 4. The nature of the heat transfer differs for each different position of the voice coil in the magnetic gap. The temperature field of the part of the coil situated inside the gap is of special interest. In this case the temperature fields are described in cylindrical coordinates by the system of differential equations

$$\frac{\partial T_i}{\partial t} = a_i\left(\frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r}\frac{\partial T_i}{\partial r} + \frac{\partial^2 T_i}{\partial z^2}\right) + \frac{w_i}{\rho_i c_i} \ (i = 1-4), \tag{1}$$

where T_i is the temperature, $a = \lambda/\rho c$ is the thermal diffusivity, w is the power of the internal heat sources, λ is the thermal conductivity, ρ is the density, c is the specific

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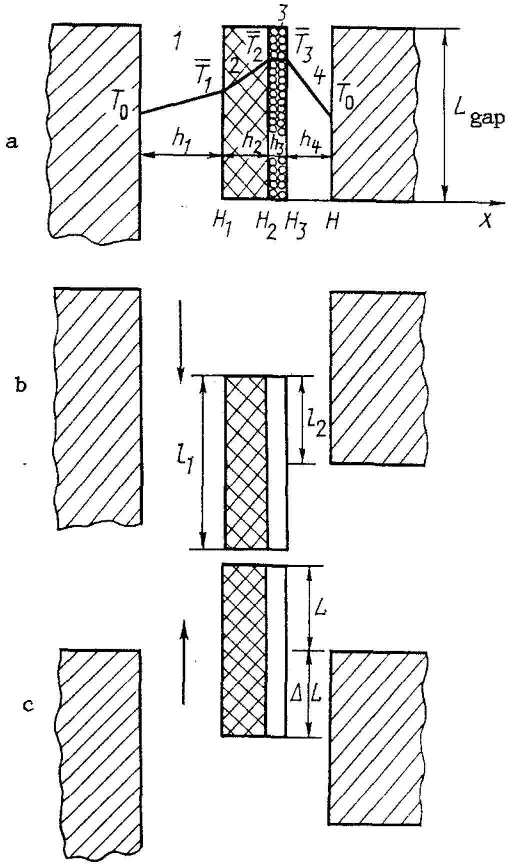

Fig. 1. Schematic analytical diagrams of heat transfer in a voice coil.

heat, and the index i signifies that the physical quantity is associated with the i-th layer.

The response of the thermal fields to change is very slow, and it is therefore sufficient to restrict the analysis to the quasisteady approximation. The left-hand sides of Eqs. (1) are approximately equal to zero in this case. Also, it follows from the small width of the gap in comparison with the radius of the coil and the height of the gap that

$$\frac{1}{r}\frac{\partial T}{\partial r} \ll \frac{\partial^2 T}{\partial r^2}; \quad \frac{\partial^2 T}{\partial z^2} \approx 0$$

(the latter relation implies the quasihomogeneous approximation). Allowing for the fact that heat release is inherent only in the voice coil, we finally obtain

$$\frac{d^2T_1}{dx^2} = 0; \ \frac{d^2T_2}{dx^2} = 0; \frac{d^2T_3}{dx^2} + \frac{q_3}{\lambda_3} = 0; \frac{d^2T_4}{dx^2} = 0, \tag{2}$$

where the coordinate x is introduced in place of r, since we are considering an essentially planar geometry.

The boundary conditions for the system (2) include thermostatic invariance on both sides of the gap (Dirichlet boundary conditions) and continuity of the temperatures and heat fluxes at the boundaries of the zones [mixed boundary conditions (boundary conditions "of the fourth kind")]:

$$T_1(0) = T_0; \ T_1(H_1) = T_2(H_1); \ \lambda_1 \frac{dT_1}{dx}\Big|_{x=H_1} = \lambda_2 \frac{dT_2}{dx}\Big|_{x=H_1};$$

$$T_2(H_2) = T_3(H_2); \ \lambda_2 \frac{dT_2}{dx}\Big|_{x=H_2} = \lambda_3 \frac{dT_3}{dx}\Big|_{x=H_2}; \tag{3}$$

$$T_3(H_3) = T_4(H_3);\ \lambda_3 \frac{dT_3}{dx}\bigg|_{x=H_3} = \lambda_4 \frac{dT_4}{dx}\bigg|_{x=H_3};\ T_4(H_4) = T_0.$$

The resulting system of ordinary differential equations can be solved by introducing new variables according to the equations

$$\Theta = T - T_0;\quad \alpha_i = \lambda_i/h_i, \tag{4}$$

transforming to them in relations (2) and (3), and taking into account the continuity of the heat fluxes at the boundaries of the zones:

$$\begin{aligned} \bar{\Theta}_1 &= \beta \frac{\alpha_2(2\alpha_3+\alpha_4)}{(\alpha_1+\alpha_2)\alpha_3^2-(\alpha_1\alpha_2+\alpha_1\alpha_3+\alpha_2\alpha_3)}; \\ \bar{\Theta}_2 &= \beta \frac{(\alpha_1+\alpha_2)(2\alpha_3+\alpha_4)}{(\alpha_1+\alpha_2)\alpha_3^2-(\alpha_1\alpha_2+\alpha_1\alpha_3+\alpha_2\alpha_3)}; \\ \bar{\Theta}_3 &= \beta \frac{\alpha_1\alpha_2+2\alpha_3(\alpha_1+\alpha_2)}{(\alpha_1+\alpha_2)\alpha_3^2-(\alpha_1\alpha_2+\alpha_1\alpha_3+\alpha_2\alpha_3)}. \end{aligned} \tag{5}$$

Equations (5) completely determine the temperature profile in the gap of the magnetic circuit. The average temperature of the voice coil in this case is

$$\tilde{\bar{\Theta}}_3 = \frac{1}{3}\int_{H_2}^{H_3} \Theta_3 dx = \frac{\bar{\Theta}_3+\bar{\Theta}_2}{2} - \frac{\beta h_3}{6\lambda_3}. \tag{6}$$

If the voice coil is made from a good heat-conducting material ($\lambda_3 \to \infty$), the parameter $\beta \to 0$, but then α_3 also tends to zero according to Eq. (4), and it is therefore more convenient to analyze the problem in the limit $\lambda_3 \to \infty$ by another method. It follows from physical considerations that $\bar{\Theta}_2 = \bar{\Theta}_3 = \Theta_3$ in this case. Accordingly, introducing the heat flux densities

$$q_1 = \lambda_1 \frac{dT_1}{dx}\bigg|_{x=H_1};\ q_2 = -\lambda_4 \frac{dT_4}{dx}\bigg|_{x=H_3}, \tag{7}$$

we obtain the system of equations

$$\alpha_1\bar{\Theta}_1 = \alpha_2(\bar{\Theta}_2-\bar{\Theta}_1);\ \alpha_4\bar{\Theta}_2 = q_2;\ \alpha_2(\bar{\Theta}_2-\bar{\Theta}_1) = q_1;\ q_1+q_2 = q, \tag{8}$$

where q is the total heat flux density.

Solving the system (8), we obtain the unknown temperatures

$$\bar{\Theta}_1 = \frac{q\alpha_2}{\alpha_1\alpha_2+\alpha_1\alpha_4+\alpha_2\alpha_4};\ \bar{\Theta}_2 = \frac{q(\alpha_1+\alpha_2)}{\alpha_1\alpha_2+\alpha_1\alpha_4+\alpha_2\alpha_4} \tag{9}$$

and the heat fluxes on both sides of the voice coil

$$q_1 = q\frac{\alpha_1\alpha_2}{\alpha_1\alpha_2+\alpha_1\alpha_4+\alpha_2\alpha_4};\ q_2 = q\frac{\alpha_4(\alpha_1+\alpha_2)}{\alpha_1\alpha_4+\alpha_1\alpha_2+\alpha_2\alpha_4}. \tag{10}$$

When the voice coil does not project beyond the edges of the magnetic gap, the numerical values of the characteristic temperatures (excess temperatures in overheating) at a dissipated power of 1 W are $\bar{\Theta}_1$ = 11.9°C and $\bar{\Theta}_2$ = 13.8°C.

In the case of an advanced coil (Fig. 1b) it follows from physical considerations, and from the fact that the overlap area of the coil surface and the magnetic circuit on the left side is very large, that heat transfer again takes place through heat conduction. In physical variables, taking into account the inequality of heat transfer on the right and left sides, we obtain

$$q_1 l_1 + q_2 l_2 = \frac{w}{2\pi R};\ \alpha_1\bar{\Theta}_1 = \alpha_2(\bar{\Theta}_2-\bar{\Theta}_1);\ \alpha_4\bar{\Theta}_2 = q_2;\ \alpha_2(\bar{\Theta}_2-\bar{\Theta}_1) = q_1. \tag{11}$$

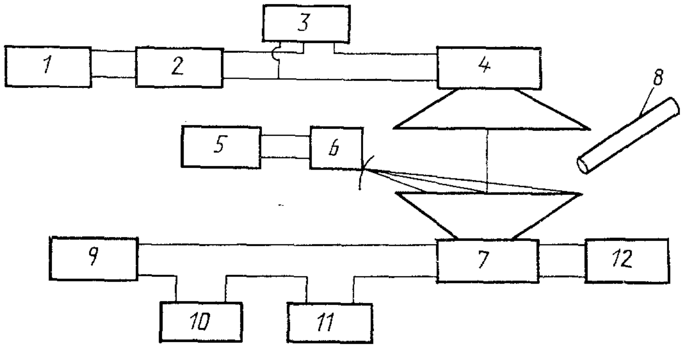

Fig. 2. Block diagram of the experimental apparatus used to investigate heat transfer for large displacements of a voice coil.

The solution of the system (11) gives the reference temperatures

$$\bar{\Theta}_1 = \frac{w\alpha_2}{2\pi R\,(\alpha_1\alpha_2 l_1 + \alpha_4\alpha_2 l_2)};\ \bar{\Theta}_2 = \frac{w\,(\alpha_1 + \alpha_2)}{2\pi R\,(\alpha_1\alpha_2 l_1 + \alpha_4\alpha_2 l_2)} \tag{12}$$

and the heat fluxes

$$q_1 = \frac{w\alpha_1\alpha_2}{2\pi R\,(\alpha_1\alpha_2 l_1 + \alpha_2\alpha_4 l_2)};\ q_2 = \frac{w\alpha_4\alpha_2}{2\pi R\,(\alpha_1\alpha_2 l_1 + \alpha_4\alpha_2 l_2)}. \tag{13}$$

Equations (12) can be used to determine the temperature of the voice coil as a function of the coil depth x. If $x < L_{VC}$, then $l_2 = L_{VC} - x$ (l_1 is always equal to L_{VC}). For example, if $L_{VC} = 5.4$ mm and $L_{gap} = 3.7$ mm, we have $\bar{\Theta}_2 = 18.7$°C.

The determination of the temperature fields for a coil that projects out of the coil gap poses a more complex problem. In this case a large part of the coil is situated outside the magnetic circuit of the dynamic transducer, where strong free convection can develop. Consequently, for the analysis we therefore use the model problem of free convection (FC) around a flat plate with the heat flux specified by Neumann boundary conditions. The dimensionless FC equations are as follows in the boundary-layer approximation without dissipation of mechanical energy:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + \Theta;\quad \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0;$$

$$u\frac{\partial \Theta}{\partial x} + v\frac{\partial \Theta}{\partial y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 \Theta}{\partial y^2} \tag{14}$$

subject to the boundary conditions (the origin is located at the lower edge of the plate)

$$u = 0;\ v = 0;\ \frac{\partial \Theta}{\partial y} = -x^{\gamma}\ \text{at}\ \ y = 0;\ u = 0;\ \Theta \to 0\ \text{as}\ \ y \to \infty. \tag{15}$$

Dimensionless variables and parameters are introduced in problem (14), (15) according to the equations

$$x = \frac{x'}{L};\ y = \frac{y'}{L}\mathrm{Gr}^{1/5};\ \Theta = \frac{(T - T_\infty)\lambda}{q_0 L}\mathrm{Gr}^{1/5};$$

$$u = u'\,[q_0 L^2 \beta_T^2\, g/\lambda]^{-1/2}\mathrm{Gr}^{-1/10};\ \mathrm{Pr} = \frac{\nu}{a};$$

$$v = v'\,[q_0 L^2 \beta_T^2\, g/\lambda]^{-1/2}\,\mathrm{Gr}^{3/10};\ \mathrm{Gr} = L^4\beta_T g q_0/\lambda\nu^2, \tag{16}$$

where the prime is attached to dimensioned variables, q_0 is a heat-flux scale, L is the length of the plate, β_T is the coefficient of thermal expansion, g is the free-fall acceleration, Pr and Gr are the Prandtl and Grashof numbers, ν is the kinematic viscosity of the medium, and γ is the heat-flux parameter (the heat flux is regarded as a variable).

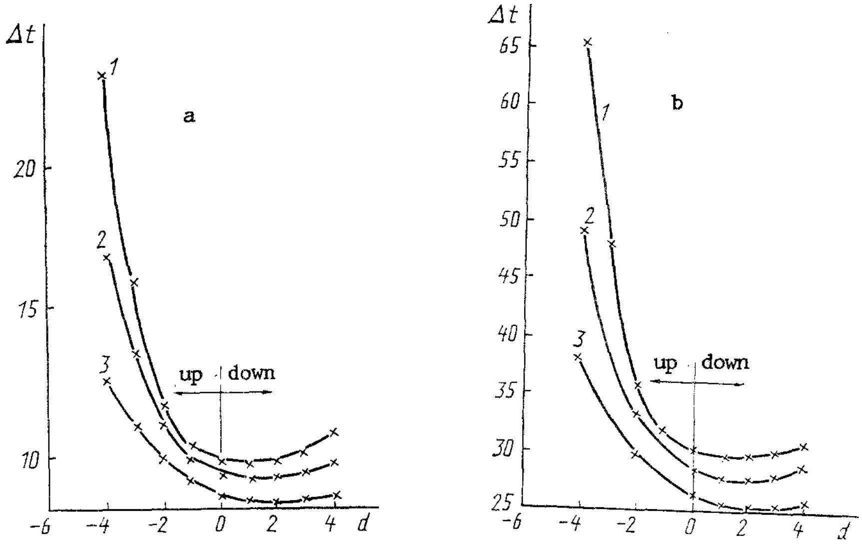

Fig. 3. Excess (overheating) temperature of the voice coil Δt (°C) vs. its displacement d (mm) at various signal power levels p and thicknesses A of the projection of the magnetic system. a) p = 1 W; b) 3 W; 1) A = 0; 2) 1 mm; 3) 2 mm.

An effective approach to the solution of this problem is the method of matched asymptotic expansions [4], which eventually yields the average excess temperature

$$\Delta T_{av} = \int_0^L \Delta T(x)\,dx = \frac{5}{6}\,g(0)\,\frac{q_0 L}{\lambda}\left(\frac{5}{4}\right)^{1/5} \mathrm{Gr}^{-1/5}\mathrm{Pr}^{-1/5}. \tag{17}$$

An important consideration is the determination of the longitudinal space scale L_a. If L_a is interpreted as the height of the part of the coil L_{vc} situated above the magnetic gap, the result is large overheating. For example, for ΔL = 3.3 mm, a total two-sided dissipated power of 1 W, and a height (L_{vc} = 5.4 mm) in air (λ = 0.025 W/m^2·K, $\nu = 16 \cdot 10^{-6}$ m^2/sec) we have ΔT_{av} = 77.7°C. In real environments, however, the leakage of heat upward through the form and its subsequent redistribution by free convection must be taken into account, which can be done by increasing the scale L_a, i.e., by introducing a scale factor α:

$$L_a = \alpha (L_{vc} - \Delta L), \quad \alpha > 1,$$

where ΔL is the length of the part of the voice coil inside the gap. The specific value of α must be determined experimentally.

We investigated heat transfer in a voice coil experimentally for large displacements of the coil, using an apparatus whose block diagram is shown in Fig. 2.

A micrometer screw in the housing of the physical loudspeaker model was used to move the simulated magnetic system 7 of the speaker relative to the voice coil by a constant prescribed amount, thereby establishing a fixed displacement of the voice coil. A signal with a specified frequency was sent from the G6-28 audio oscillator 1 through the U-100 power amplifier 2 to the driving speaker 4. The power demand was monitored by the F-585 wattmeter 3. The oscillations of the driving speaker imparted periodic motion to the cone of the speaker model through a rigid rod. The amplitude of the oscillations was determined by means of the microscope 8 in conjunction with the strobe light 6 and the G5-54 oscillator 5. A signal with a specified power was sent from the IPS-1 power supply 9 through the D-57 dc wattmeter 10 and M20-15 voltammeter 11 to the voice coil of the model speaker. The R-385 voltfaradmeter 12, which measured the impedance of a sensor inserted between the layers of the voice coil, was used to determine its temperature for various combinations of the constant displacement, oscillation amplitude, and signal level.

The magnetic system of the speaker was made of a nonmagnetic material (aluminum) for these investigations. The diameter of the upper disk of the magnetic system was slightly greater than the height of the voice coil (the thickness of the disk was 8 mm, and the height of the coil was 7.3 mm). The micrometer screw in the magnetic system simulator of the speaker was used to move the simulator ±4 mm relative to the voice coil, i.e., by a distance equal to half the height of the coil. The frequency of the voice coil oscillations was set at 30 Hz, and their amplitude was set at 2 mm and 4 mm. The power of the dc signal sent to the voice coil had values of 1 W and 3 W (Fig. 3). The graphs of the excess temperature of the voice coil as a function of its position in the gap of the magnetic system of the speaker at various oscillation amplitudes and power imputs lead to the following conclusions.

If oscillations are absent and the voice coil is in the middle position, it never exceeds the limits of the gap in the magnetic circuit (in our experiment the gap was the space between the upper disk and the core of the magnetic system of the speaker). The heat-transfer conditions are optimal in this case. Heat transfer takes place by heat conduction through the air layer on one side, the cardboard of the form, and the air layer on the other side. Since the thicknesses of all these layers are very small, as are their thermal resistances (the characteristic parameters α_i are very large), overheating of the coil is insignificant.

When the voice coil is moved inside the magnetic system, the heat-transfer conditions deteriorate, because thermal contact (through the gap) with the upper disk is lost. However, inasmuch as the conditions of heat transfer with the core of the magnetic system do not change, the heat flux is simply redistributed, and the temperature of the voice coil increases only very slightly, consistent with the results of the theoretical calculations. When the voice coil is moved outside the gap, thermal contact is lost both with the upper disk and with the core of the magnetic system. Now the coil is cooled by free convection. However, free-convection heat transfer is far less efficient, and so the overheating of the coil is very high, attaining 65°C under our experimental conditions. The generation of oscillations of the voice coil intensifies heat transfer, but the behavior of the excess temperature as a function of the position of the voice coil does not change.

In the experiment, the temperature of the voice coil during variation of the constant displacement and the frequency of the periodic displacement of the coil in the speaker model at a given heating power was determined from the equation

$$\rho_t = \rho_0 (1 + \alpha t),$$

where ρ_0 is the resistivity of the sensor at 0°C, α is the temperature coefficient of resistance of the sensor, and t is the temperature of the current-carrying wire. The excess temperature of the coil was then plotted as a function of the constant and periodic displacements for various signal power levels (Fig. 3).

A comparison shows that the experimental data confirm the conclusions of the theoretical analysis. We have shown that the rate of heat transfer depends strongly on a particular design factor: the position of the coil in the gap. The most favorable regime is conductive heat transfer, when the coil is situated in the narrow gap of the magnetic system of the speaker. This fact points the way to possible design solutions from the point of view of enhancing the heat-transfer rate. Other solutions are possible as well, for example, by setting up forced convection. This and other approaches will be discussed in our next paper.

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