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Optimizing parameters of speech signals condenser sensor by inner noise of the receiving channel

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Abstract. Noise characteristics of the receiving electroacoustic channel with an electret condenser sensor of speech signal have been considered in the paper. The technique for optimizing the converter' characteristics by inner electrical noise of the signal amplifier as well as the sensor's experimental amplitude-frequency response have been given. It has been found that in order to suppress noise generated by the amplifier it is advantageous to have a Q -factor within $2 \div 4$ and resonance frequency ω_0 in the range of $0.7 \div 0.85 \omega_2$ in the condenser converter.

1. Introduction

To receive electroacoustic signals from a speech signal object the contact-type sensor converters, or laryngophones are used [1]. When designing a receiving channel of the electroacoustic systems for speech signals the rational function distribution of a given amplitude-frequency characteristic (AFC) formation of the entire receiving channel between the receiving sensor converter and the signal amplifier is of vital importance. With regard to the electroacoustic converter (microphone or laryngophone), the AFC is determined by its design type, for example, condenser sensor, which has the characteristic features of the parameters of the active element in the operating frequency range.

In practice, it is possible to use the concept of the formation of the receiving channel's given AFC when the electroacoustic condenser converter provides the greatest possible given frequency characteristic, and the amplifying channel forms cutoffs at the frequencies ω_1 and ω_2 (Figure 1). Since the mechanical system of electroacoustic condenser converter 1 (Figure 1) does not always provide the given AFC of the channel, the quadrupole 3 adjusting AFC with the characteristic being reverse of the converter's 1 is placed at the output of the linear previous amplifier 2. The quadrupole 3 forms AFC (as a resultant one) with the constant coefficient of transmission of the entire receiving channel in the operating frequency range of $\omega_1 \div \omega_2$.



Figure 1. Structural diagram of the receiving channel for the acoustic sensor converter signal gain: 1 – condenser converter of the acoustic signal; 2 – previous linear amplifier; 3 – adjusting quadrupole; 4 – power amplifier; 5 – output signal.

2. Equivalent sensor circuit

For the formation of the channel's uniform AFC let us select the inertial-type electret condenser convertor's (laryngophone's) parameters (Q – factor and resonant frequency ω) for maximum protection against the inner noise, having its origin in the speech signal receiving system. To do this, we use its equivalent electric circuit model in the form of a series of R, L, C -circuits (Figure 2a) [1].

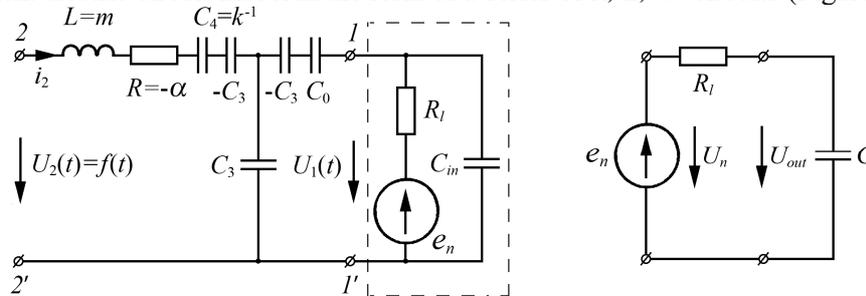


Figure 2. Equivalent circuit of the replacement of electret condenser laryngophone.

3. Amplifier input circuit noise

Input (noise) active resistance R_l of the linear preamplifier can be represented by the equivalent circuit (Figure 2b), which includes the noise-free resistance R_l and the emf source ($e_n = U_n$), connected in series (C_{eq} – equivalent capacitance 1-1'(Figure 2a). The instantaneous value of emf is usually characterized by the mean value on the time by the square of its value, referring to the actual value.

$$\overline{U_n^2} = U_n^2 = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T U_n^2(t) dt, \tag{1}$$

$$U_n = \lim_{T \rightarrow \infty} \sqrt{\frac{1}{2T} \int_{-T}^T U_n^2(t) dt}. \tag{2}$$

It is known that if the source of the noise possessing spectral power density $N(\omega)$, operates at the linear quadrupole input with the transfer function $K_1(j\omega)$, then the noise power at the output of the quadrupole 3 Figure 1 is equal to:

$$U_{out} = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} N(\omega) |K_1(j\omega)|^2 d\omega, \tag{3}$$

where $\omega_1 \div \omega_2$ is the quadrupole pass band.

Using equation (3) it is possible to calculate the noise level at the output of the amplifier 2 (Figure 1) generated by the e_n source at the bandwidth within its operating frequencies range of $\omega_1 \div \omega_2$. The characteristic of the amplifier is taken as being ideally rectangular with the gain coefficient equal to 1.

When calculating the transmission coefficient $K_1(j\omega)$ of the sensor we consider the input clamps of the equivalent circuit (Figure 2a) as the emf e_n , while the output ones is 1-1'. In this case, the input 2-2' is short-circuited. For the low frequency region, we can assume that the part of the converter's equivalent circuit, which is parallel to the noise resistance has an absolute capacitive resistance $C = C_0 + C_{in}$. Then the expression for the transmission coefficient of the sensor $K_1(j\omega)$ can be written as:

$$K_1(j\omega) = \frac{1/j\omega C}{R_l + 1/j\omega C} = \frac{1}{1 + j\omega R_l C}, \tag{4}$$

Then the expression for the noise voltage U_{out}^2 in action can be presented as

$$U_{out}^2 = \frac{4kT_0 R_l}{2\pi} \int_{\omega_1}^{\omega_2} \frac{d\omega}{1 + \omega^2 (R_l C)^2} = \frac{2kT_0}{\pi C} [\arctg \omega_2 R_l C - \arctg \omega_1 R_l C]. \tag{5}$$

From (5) it is quite clear that U_{out}^2 depends on the amplifier bandwidth $\omega_1 \div \omega_2$. If $\omega_1 = 0$ and $\omega_2 = \infty$, the value U_{out}^2 takes its maximum.

$$U_{out.m}^2 = \frac{2kT}{\pi C} \cdot \frac{\pi}{2} = \frac{kT_0}{C}. \quad (6)$$

Let us consider the expression for the normalized effective value of the noise voltage with respect to the square maximum as:

$$U_{out}^2 / U_{out.m}^2 = m^2 = \frac{2}{\pi} [\arctg \omega_2 R_l C - \arctg \omega_1 R_l C]. \quad (7)$$

It follows from (7) that at the amplifier output the effective noise level m^2 depends on $\omega_1 R_l C$ nonlinearly. So at the constant frequency ω_1 in terms of $R_l C \gg 1/\omega_2$ (when ω_2 is set by the amplifier) the first term in the brackets $\arctg(\omega_1 R_l C) \approx \pi/2$ is constant, and the second $\arctg(\omega_1 R_l C)$ increases with an increase in R_l . At the same time m^2 decreases. If $R_l C = 1/\omega_1$, which is usually recommended, m^2 is reduced by half, if $R_l C = 5/\omega_1$, m^2 reduces by 5 times. When $R_l C = 10/\omega_1$ m^2 decreases by 9.3.

The graphical function analysis of noise power spectral density at the amplifier output written in the form of

$$S(\omega) = |K_1(j\omega)|^2 \cdot N_0 = \frac{4kT_0 R_l}{1 + \omega^2 (R_l C)^2} \quad (8)$$

shows that to reduce noise one needs to increase R_l so that the lower frequency limit ω_{ow} of the converter would shift to a low frequency region to be several times less than the given ω_1 value for the speech range.

4. Sensor's parameters optimization at noise suppression in the channel

The electret sensor converter is not directly involved in the suppression of the noise generated by the amplifier 2 Figure 1. However, the noise from the preamplifier 2 pass through the adjusting quadrupole 3. The noise level at its output depends on the transmission function $W(j\omega) = 1/K(j\omega)$, which is determined by the transfer function of the condenser converter $K(j\omega)$. When $\omega R_l C_{in} \gg 1$ $K(j\omega)$ is written in the form of:

$$K(j\omega) = K(0) \sqrt{\left[(j\eta)^2 + \frac{j\eta}{Q} + 1 \right]}, \quad (9)$$

where: $K(0) = E_{10} \frac{C_0}{C_0 + C_{in}} \cdot \frac{1}{\chi}$; $\chi = K - E_{10}^2 \frac{C_0 C_{in}}{C_0 + C_{in}}$; $\omega_0 = \sqrt{\chi/m}$; $Q = \sqrt{m\chi}/\alpha$; $\eta = \omega/\omega_0$;

m , ω_0 and χ – are mass, resonance frequency and coefficient of elasticity of the oscillatory system, respectively; α – the total coefficient of friction of the mechanical system; E_{10} is the electric field strength in the air gap between the electret film and the counter electrode.

According to (9), the converter at large R_l is a system of the 2nd order and its transfer function is similar to the transmission function of the adjusting quadrupole assembled on the RLC -circuit. Since here, the ω_0 values and Q -factor are relevant to the resonant frequency and quality of the converter electromechanical system we conduct the optimization in terms of suppression of noise, generated by the amplifier.

The noise generated by the amplifier can be taken into account by including noise from the emf source at its input, which is characterized by a certain function of the noise power spectral density $N_a(\omega)$ that for electric circuits on semiconductors in some cases is represented by a polynomial in powers of ω :

$$N_a(\omega) = a_0 + a_1 \omega^{-1} + a_2 \omega + a_3 \omega^2. \quad (10)$$

To solve the task of optimization of the function $W(j\omega)$, it is necessary to consider the noise power at the output of the system both without the adjusting quadrupole and in its presence. Here, the passage of each noise component should be considered separately.

Noise component $N'_a(\omega) = a_0$

For the output noise power in the absence of an adjusting quadrupole the following expression is true:

$$P_{out} = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} N_a(\omega) d\omega = \frac{a_0}{2\pi} (\omega_2 - \omega_1), \quad (11)$$

while in its presence it is represented as:

$$\begin{aligned} P_{out}^* &= \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} a_0 \left[1 - (2 - Q^{-2})\eta^2 + \eta^4 \right] d\omega = \\ &= \frac{a_0}{2\pi} \left[(\omega_2 - \omega_1) - \frac{\omega_2^3 - \omega_1^3}{\omega_0^2} \cdot \frac{2 - Q^{-2}}{3} + \frac{\omega_2^5 - \omega_1^5}{5\omega_0^4} \right]. \end{aligned} \quad (12)$$

Let us consider the expression (8) for at least three different ways of changing the parameters of the converter: a) resonance frequencies ω_0 in a fixed Q -factor; b) parameter χ at $m = \text{const}$, $\alpha = \text{const}$; c) oscillatory system' mass m at $\chi = \text{const}$, $\alpha = \text{const}$.

Mode $\omega_0 = \text{var}$, $Q = \text{const}$. When $\omega_2 \gg \omega_1$ we get

$$\frac{dP_{out}^*}{d\omega_0} = \frac{a_0}{2\pi} \left[\frac{\omega_2^3}{3\omega_0^2} \cdot 2(2 - Q^{-2}) \frac{4}{5} \frac{\omega_2^5}{\omega_0^5} \right]. \quad (13)$$

From where we have the expression for the relative value of the optimal resonance frequency:

$$\frac{\omega_{r.o}}{\omega_2} = \sqrt{\frac{6}{5} \frac{1}{2 - 1/Q^2}}. \quad (14)$$

In this case the value P_{out}^* is

$$P_{out.o}^* = \frac{a_0}{2\pi} \left[(\omega_2 - \omega_1) - \frac{5}{36} \omega_2 (2 - Q^{-2})^2 \right]. \quad (15)$$

The ratio $P_{out.o}^* / P_{out} = Q_o^2$ shows the degree of noise suppression at the expense of passing through the adjusting quadrupole.

$$Q_o^2 = \frac{\frac{a_0}{2\pi} (\omega_2 - \omega_1)}{\frac{a_0}{2\pi} \left[(\omega_2 - \omega_1) - \frac{5}{36} (2 - Q^2)^2 \right]} \Bigg|_{\omega_2 \gg \omega_1} \approx \left[1 - \frac{5}{36} (2 - Q^2)^2 \right]^{-1}. \quad (16)$$

Similar treatment and numerical calculations have been carried out when using other methods of changing the converter's parameters (b) and (c) for all components (10) of the noise generated by the amplifier.

The analysis of the optimization results has demonstrated that to suppress noise, generated by the amplifier, in the condenser converter it is reasonable to have Q -factor in the range of $2 \div 4$, and the resonance frequency ω_0 within the limits of $0.7 \div 0.85 \omega_2$.

5. Experimental results

Samples of laryngophone-type electret capacitance sensor converters, based on the electret film elements 5 have been made experimentally (Figure 3). The electret film 5 is made from fluoropolymer, obtained through the deposition (condensation) from the active gas phase while spraying the initial

polytetrafluoroethylene in HF-plasma discharge [2, 3] or HF-magnetron [4, 5]. The film thickness was $6 \div 8 \mu\text{m}$ thick.

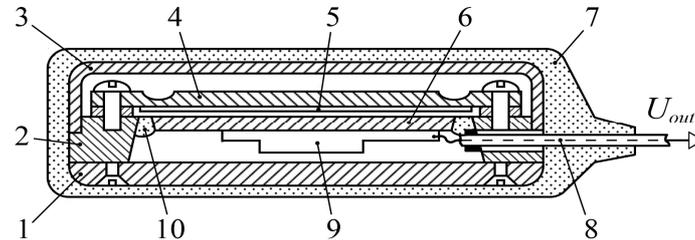


Figure 3. The design of the condenser sensor of speech signals: 1, 2, 3 – parts of sensor housing; 4 – vibrating electrode; 5 – electret film element; 6 – counter electrode; 7 – sealant; 8 – the output of the previous amplifier; 9 – previous amplifier; 10 – counter electrode insulator.

Another way of making the electret element was a planar two-layer structure on a silicon substrate. The first structure layer was made of silicon oxide of $0.7 \div 0.9 \mu\text{m}$ thick, and the outer layer as a protective one was made from F-parylene of $0.2 \div 0.5 \mu\text{m}$ thick. The samples were polarized in corona discharge in strong electric fields, and then were surface charge stabilized at the temperature of 120°C . The layered electret elements at higher operating temperatures ($60 \div 100^\circ\text{C}$) showed higher stability of the $U(t)$ surface potential.

The electret condenser converter has parameters close to the calculated ones ($\omega_0 = 2.7 \text{ kHz}$ and $Q = 2.7 \dots 3.4$). Typical AFC of the electret speech signals converter is shown in Figure 4. Here: curve 1 – an ideal AFC with due regard for a man's throat vibrations; 2 – AFC of the electret condenser laryngophone; 3 – AFC of the same electromagnetic-type sensor laryngophone.

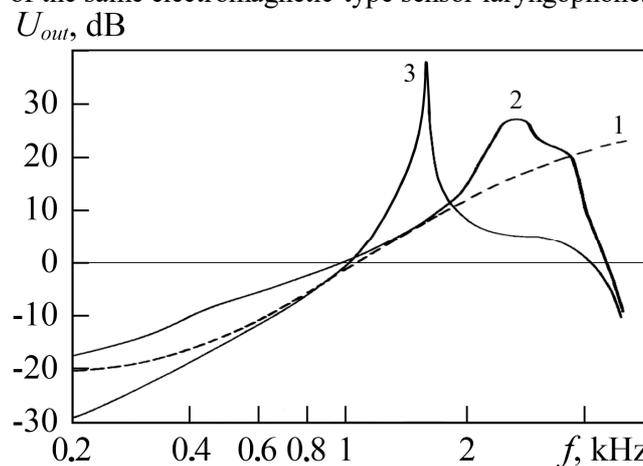


Figure 4. AFC of the condenser sensor of speech signals.

6. Conclusion

The authors have considered noise characteristics of the receiving channel from the electret speech signals condenser converter with the AFC adjusting quadrupole's linear preamplifier placed at the converter's output. The quadrupole characteristic is inverse to the converter's. The parameters of the converter with the greatest protection against the inner noise arising in the electret laryngophone's system of reception and transmission have been analyzed. For effectively suppressing noise generated by the amplifier the sensor condenser converter should have a quality factor Q in the range of $2 \div 4$, and the self-resonant frequency ω_0 in the region of $0.7 \div 0.85 \omega_2$. It was experimentally found that electret

condenser converter of the inertial type (laryngophone) has the optimum frequency response of the channel with high interference immunity at good intelligibility of speech in the range of $100 \div 4500$ Hz.

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