Thermal Noise in Microphones and Preamplifiers

by

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ABSTRACT

The smallest sound pressure that could be measured by condenser and piezoelectric microphones was in the past determined by the noise from their preamplifiers. However, the development of preamplifiers have reached a stage where their noise is less than the noise generated by the thermal vibrations of the membrane. This is shown experimentally by measuring the dependency of noise voltage on temperature. The experimental observation is compared with a computation of the noise voltage.

The noise sources in modern preamplifiers are discussed and the noise spectrum of the whole sound receiving system is given.

SOMMAIRE

La plus faible pression acoustique mesurable à l'aide de microphones électrostatiques ou piézoélectriques était, par le passé, fixée par le bruit engendré dans les préamplificateurs. Cependant, les développements des préamplificateurs ont été tels que leur bruit est maintenant inférieur au bruit engendré par les vibrations thermiques de la membrane.

Ce phénomène est montré expérimentalement en mesurant la relation entre la tension de bruit et la température. Les résultats expérimentaux sont comparés aux calculs de la tension de bruit.

On discute les sources de bruit des préamplificateurs modernes et on donne le spectre de bruit du récepteur acoustique global.

ZUSAMMENFASSUNG

Der kleinste Schalldruck, der mit einem Kondensator- oder Piezomikrofon gemessen werden konnte, war bisher durch das Rauschen der verwendeten Vorverstärker bestimmt. Die Entwicklung der Vorverstärker hat jetzt jedoch ein Stadium erreicht, wo deren Eigenrauschen geringer ist als das Rauschen, das durch thermische Bewegung der Membran hervorgerufen wird.

Dies wird experimentell durch Messung der Abhängigkeit der Rauschspannung von der Temperatur nachgewiesen. Das Ergebnis wird schließlich mit einer Berechnung der Rauschspannung verglichen.

Die Rauschquellen in modernen Vorverstärkern werden diskutiert, und das Rauschspektrum des gesamten Schall-Empfangssystems wird erläutert.

Introduction

In a well designed sound receiving system with condenser or piezoelectric microphones there are two important sources of thermal noise which limit the ultimate performance of the system. The first is noise from the microphone generated by the Brownian movements of the membrane. The second is electronically generated noise in the preamplifier associated with the microphone.

A typical sound measuring system consists of a microphone, a preamplifier, an amplifier and a detector with a meter on which a root mean square voltage can be read. The frequency response of the electronic system is often complicated and different responses are used.

Therefore it is most instructive to consider noise sources in terms of the noise spectra. From the spectra the output noise voltage of a system may be computed, when its frequency response is known.

In the first part of this paper the noise spectra and noise voltages of the microphones are computed. In the second part a measurement of the noise voltage is described and in the third part the noise from the preamplifiers is computed and the noise from microphones and preamplifier is added.

Computation of Noise Voltage from Microphones

Information about the output voltage from a microphone due to Brownian movements of its membrane is desired. What may be computed are the two statistical quantities, the spectral density and the mean square voltage. These may be found from the corresponding values for the deflection of the membrane.

The membrane of the condenser microphone is a mechanical system with many degrees of freedom. However, it is sufficiently accurate to use only one degree of freedom for the present case.

The generalized space coordinate is taken to be equal to the volume displacement which is equal to the integral of the deflection of the membrane over the surface of the membrane. The generalized momentum associated with this volume displacement is equal to the pressure.

In the paper by H.B. Callen and T.R. Welton (1951) ref. 1, it is shown that the statistical properties of the dynamic system may be computed by using a generalized Nyquist formula. It is assumed that a pressure with mean square value, $\Delta\overline{p^2}$ given in formula (1), is applied to the membrane.

$$\Delta\overline{p^2} = 4\,kT\,\mathrm{Re}\,[Z]\,\Delta f \qquad (1)$$

where k is the Boltzmann constant
T is the absolute temperature
Δf is the frequency bandwidth
Z is the acoustic impedance of the membrane defined in formula (2)

If the volume displacement is v and the pressure p one has

$$p = Z(\omega)\, i\omega v \tag{2}$$

The spectral density of the volume displacement may be obtained from formulas (1) and (2):

$$\overline{\Delta v^2} = 4\,kT\, \frac{\mathrm{Re}\,[Z(\omega)]}{\omega^2\, |Z(\omega)|^2} \Delta f \tag{3}$$

The mean square value of the volume displacement is found by using a statistical mechanics law which states that the mean value of the potential energy of a harmonic oscillator equals 1/2 kT. The stiffness, s, is introduced by

$$s = \lim_{\omega \to 0} i\omega Z(\omega) \tag{4}$$

It may be shown that s is real, see ref. 2.

The mean potential energy equals $1/2\,\overline{sv^2} = 1/2\,kT$, from which the following is obtained

$$\overline{v^2} = kT/s \tag{5}$$

This could be obtained from formula (3) by integrating the expression over all frequencies. This is shown in L.P. Landau and E.M. Lifschitz, ref. 2.

The open circuit voltage of the microphone is proportional to the volume displacement, that is

$$e = cv \tag{6}$$

where the constant, c, is independent of frequency. It is related to the pressure sensitivity, $F(\omega)$ defined by*)

$$e = F(\omega)\, p \tag{7}$$

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* $F(\omega)$ is known from the measurements of the microphone pressure sensitivity with the electrostatic actuator. With this a constant pressure across the membrane is obtained by an electrostatic field.

By substituting the expression (2) for p in (7) and comparing it with (6) one obtains

$$c = F(\omega)\, i\omega Z(\omega) \tag{8}$$

but c does not depend on frequency and, therefore, using expression (4)

$$c = F(0)\, s \tag{9}$$

From formulas (3), (6) and (8) one obtains the spectrum for the output voltage

$$\Delta\overline{e^2} = |F(\omega)|^2\, 4\,kT\, \mathrm{Re}\,[Z(\omega)]\, \Delta f \tag{10}$$

By taking the mean square of both sides of formula (6) we have

$$\overline{e^2} = c^2 \cdot \overline{v^2} \tag{11}$$

By inserting formulas (3) and (9) in (11) we obtain

$$\overline{e^2} = F^2(0)\, skT \tag{12}$$

In the following it is assumed that the acoustic impedance has the form

$$Z(\omega) = (s + i\omega r - m\omega^2)/i\omega \tag{13}$$

where the parameters r and m are independent of frequency.

The noise voltages and pressures for some Brüel & Kjær microphones are shown in table 1. The values of sensitivity, stiffness and resistance have been obtained from the instruction manuals. The stiffnesses and resistances are directly given in the manuals for the microphones types 4144, 4145 and 4134. For the other condenser microphones the stiffness values have been estimated from the equivalent volumes given in the manuals. The parameters for the piezoelectric microphone Type 4117 were given by K. Styhr Hansen (1968), ref. 3.

The noise voltage e_n in table 1, should be used when a wide band amplifier is used. The noise voltage e_A has been obtained by assuming that the frequency response is of type A, which is recommended by various standards.

The amplification is taken to be 1 at 1000 Hz. The pressures given in table 1 have been obtained from the voltage by division by the sensitivity of the microphones.

Microphone	Sensitivity F	Stiffness s	Resistance r	Voltage e_n	Pressure $p_n = e_n/F$	Voltage e_A	Pressure $p_A = e_A/F$
	10^{-3} V/(dyn/cm^2)	10^6 dyn/cm^5	dynsec/cm^5	10^{-6} Volt	10^{-4} dyn/cm^2	10^{-6} Volt	10^{-4} dyn/cm^2
4144 1 inch	5	10.4	180	3.3	6.6	3.3	6.6
4145 1 inch	5	11.1	447	3.3	6.6	3.3	6.6
4133 1/2 inch	1.25	170	3030	3.3	26	2.5	20
4134 1/2 inch	1.25	170	1540	3.3	26	2.4	19
4148 1/2 inch	1.25	21	640	1.2	9.3	1.2	9.6
4177 piezoelec.	0.3	4.6	257	0.13	4.3	0.13	4.2

Tabel 1.

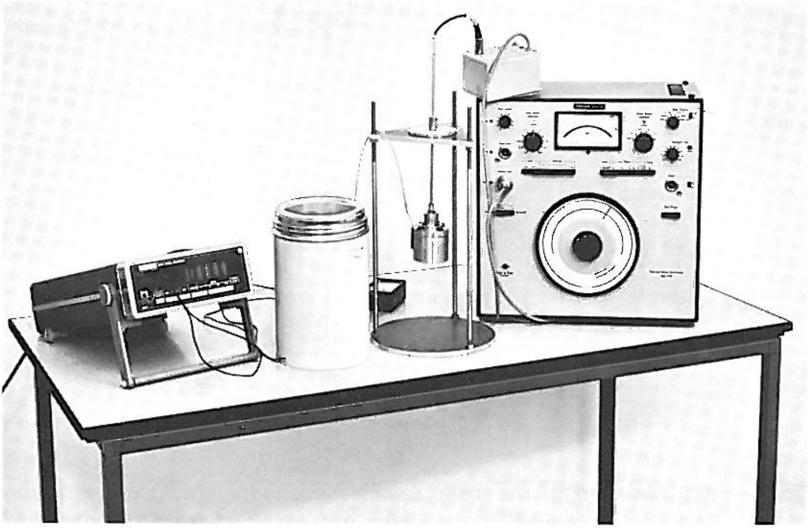

Fig. 1. The experimental arrangement for measuring the thermal noise from microphones. In the centre of the picture the brass cylinder containing the microphone hangs in a thin steel tube. Through the tube a cable is drawn which connects the condenser microphone to the preamplifier. The preamplifier is connected to the spectral analyzer at the right of the picture. When noise is measured the Dewar vessel is filled with liquid Nitrogen and the cylinder is placed in the Dewar. The temperature of the cylinder is read on the instrument to the left, which is connected to a platinum resistor placed on the brass cylinder.

Measurements of the Noise from Microphones

The noise voltage from preamplifiers are at present so low that noise from microphones should be considered. This is shown experimentally by measuring the noise voltage from a one inch condenser microphone. The microphone was mounted in a thick-walled brass cylinder, which was sealed airtight. The experimental set-up is shown on Fig.1. The microphone was connected via a preamplifier to a spectrum analyzer from which a root mean square output voltage was obtained. The brass cylinder was cooled by means of liquid nitrogen in a Dewar vessel. The temperature of the microphone was measured with a Platinum resistance thermometer and the preamplifier was kept at a constant temperature. With this arrangement the noise voltage was measured as a function of temperature as presented in Fig.2.

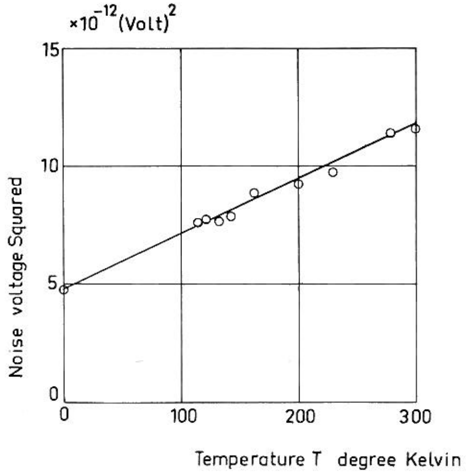

Fig.2. The variation of the mean square noise voltage with temperature. The plotted points in the figure are obtained from the observed voltages divided by a factor equal to the amplification of the open circuit voltages from the microphone. The squared voltages are the sums of the squared voltages of readings from 1/3 octave filters. The filters used covered the frequency range from 400 to 20.000 Hz, but a correction has been made in order to extrapolate to a frequency range from 0 to 20.000 Hz. The ordinate at the point at 0 degree absolute temperature was measured by replacing the microphone by a capacitor which had the same capacitance as the microphone. This point represents the electronic noise voltage from the preamplifier

The noise from the preamplifier does not depend on the temperature of the microphone. Therefore the temperature variation of noise voltage is due to microphone noise alone and the noise voltage curve shows the temperature variation to be expected from thermally generated vibrations of the diaphragm.

From Fig.2 it is easy to find the measured root mean square voltage due to thermal vibrations, it is 2,7 μV at 27°C. (The value is the open circuit voltage of the microphone). The computed value for the used microphone was 2,9 μV.

The frequency spectrum of the noise from the microphone is shown in Fig.3. The square of the noise voltage from the electronic system has been subtracted. The variation with frequency is similar to the variation of the sensitivity, within the experimental errors. This would be expected from the theoretical considerations above.

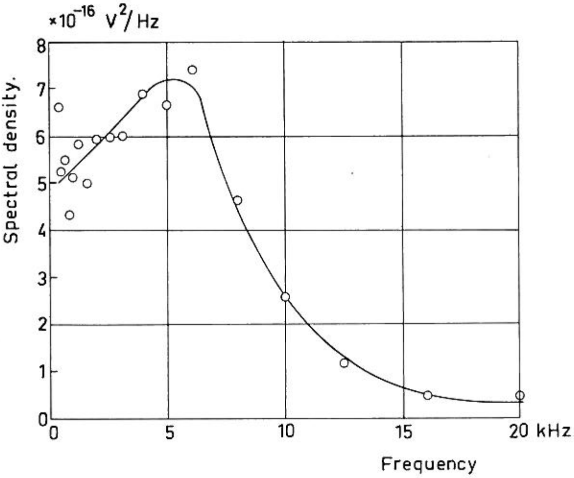

Fig.3. Frequency spectrum of thermal noise from a one inch condenser microphone Type 4144. Given is the mean square of the open circuit voltage. The nominal polarization voltage was used

Noise of preamplifiers and microphones

An idealized preamplifier circuit is shown in Fig.4. The amplifier incorporates a junction field effect transistor. If the whole measuring system is well designed, noise from the source resistor and the noise from the amplifier following the preamplifier may be neglected. The input capacitance of the preamplifier is disregarded in the following discussion, and the voltage amplification of the preamplifier is taken to be 1.

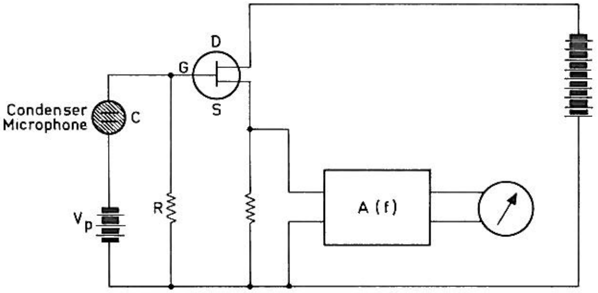

Fig.4. Simplified sketch of the preamplifier circuit

There are four main noise sources. Nyquist noise from the resistor in the gate circuit, shot noise from the gate current, noise from the channel of the field effect transistor, and "1/f" noise from the transistor.

In the frequency range of interest the noise output voltage may be computed from the following formula, given by R.S.C. Cobbold ref.4.

$$\Delta\overline{V^2} = \left[\frac{1}{C^2\omega^2}\frac{4\,kT}{R} + \frac{1}{C^2\omega^2}\,2\,q\,J_G + \frac{0.65}{g_m}\,4\,kT + \frac{A^2}{f}\right]\Delta f \qquad (14)$$

where		
	C	is the capacitance of the transducer
	ω	is the cyclic frequency
	R	is the gate resistor
	q	is the electronic charge
	J_g	is the gate leakage current
	g_m	is the conductance of the transistor
	A	is a constant for the value of the 1/f noise
	Δf	is the frequency bandwidth

In order to minimize the shot noise it is important to have a small value of the gate current. The gate resistor should be as large as possible. Its magnitude is limited by the gate current because it is necessary to have a small voltage drop across the gate resistor, and the gate current depends strongly on temperature.

The following figures are used $i_{gs} = 2 \cdot 10^{-12}$A, $R = 10^{10}$ohm. The last two terms, in (14), were obtained from information given by a transistor manufacturer.

The noise voltage spectral density from the preamplifier is given in Figs.5, 6 and 7. The curves were computed from the formula above. The mean square output voltage from the measurement system may be found from

$$\overline{V^2} = \int_0^\infty A^2(f)\, v_f^2\, df \qquad (15)$$

where A(f) is the voltage amplification of the amplifier and $v_f{}^2$ the squared noise voltage density at the input. The ability of the system to detect small sound pressures is not changed when A(f) is multiplied by a constant factor, because the signal and the noise are amplified by the same factor; and the amplification is, therefore, taken to be 1 at 1000 Hz.

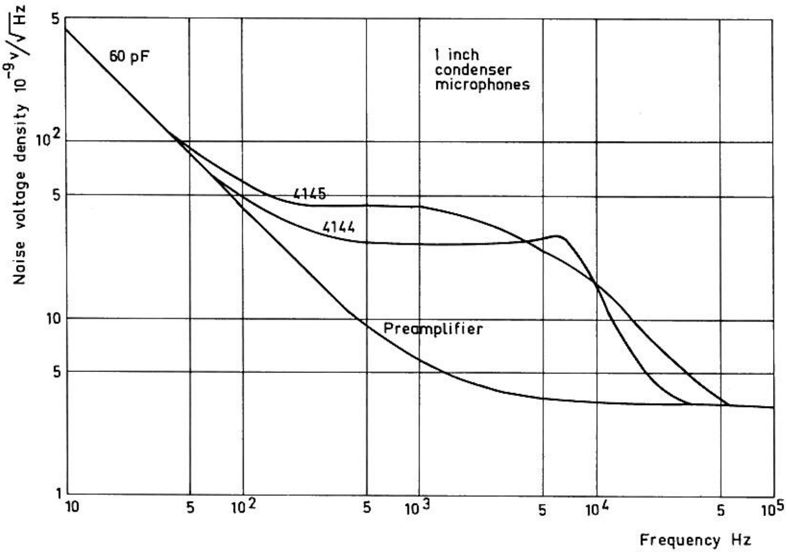

Fig.5. *The noise voltage spectral density for one inch condenser microphones and the preamplifier. The upper curves present the noise of the whole system, and the lowest curve the noise of the preamplifier alone*

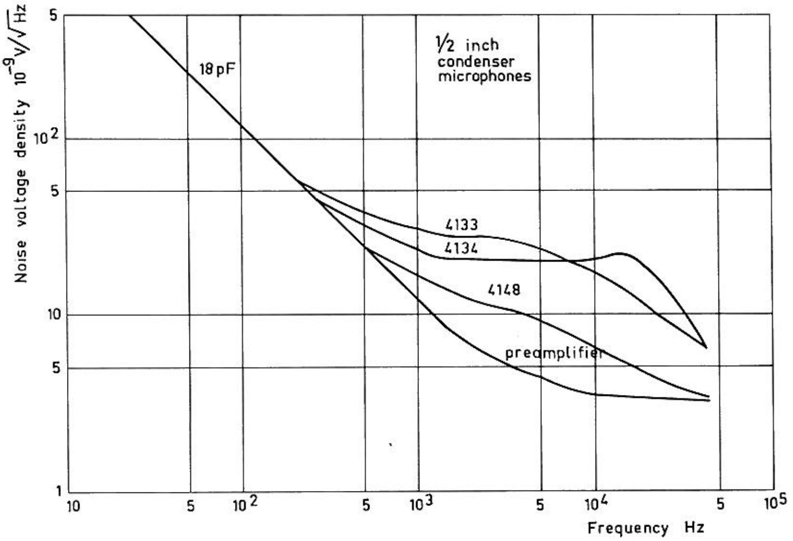

Fig.6. *The noise voltage spectral density for half inch condenser microphones and the preamplifier. The lowest curve presents the noise of the preamplifier alone*

The relative importance of the different noise sources may be estimated from a numerical example of the computation of the mean square noise voltage

$$\overline{\Delta V^2} = (51.7 \cdot 10^{-14} + 21.5 \cdot 10^{-14} + 18 \cdot 10^{-14} + 2.7 \cdot 10^{-14})\ (\text{Volt})^2 \qquad (16)$$

the terms are written in the same order as in the formula above. The capacity of the microphone is C = 60 pF, the frequency response is taken to be constant from 20 Hz to 20.000 Hz, outside this interval it is zero.

The noise voltages from the preamplifier with different microphones are shown in table 2. The wide band frequency response is from 20 Hz to 20.000 Hz for the microphones Types 4144, 4145 and 4117 and from 20 Hz to 200.000 Hz for Types 4133, 4134 and 4148. There is only a small change in noise voltage from the preamplifier when changing from the small bandwidth to the large. The shift in noise voltage is from 2,9 μV to 3,2 μV with a 18 pF microphone capacitance.

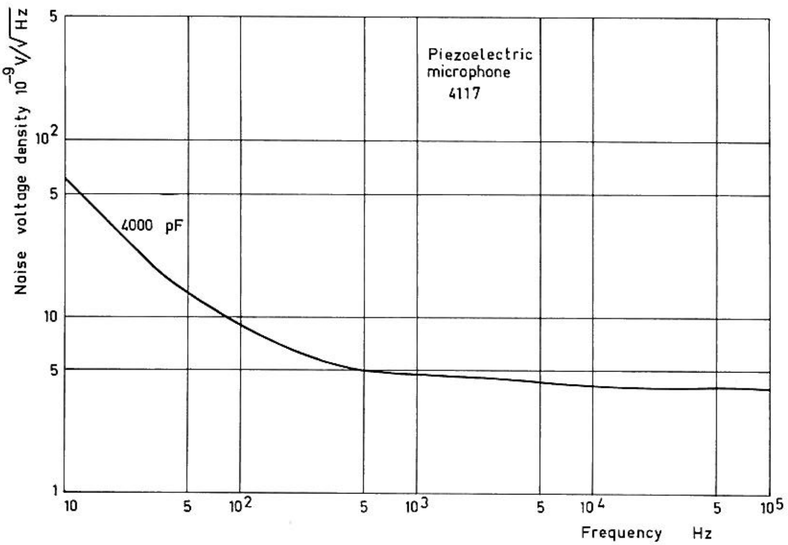

Fig. 7. The noise voltage spectral density for the preamplifier with the piezoelectric microphone. The noise from the microphone may be neglected

Microphone	Capacity	Wide band frequency response			Type A frequency response		
		Preamplifier	Preamplifier and Microphone	Total noise pressure	Preamplifier	Preamplifier and microphone	Total noise pressure
	pF	10^{-6} Volt	10^{-6} Volt	10^{-4} dyn/cm^2	10^{-6} Volt	10^{-6} Volt	10^{-4} dyn/cm^2
4144	60	1.0	3.4	6.8	0.3	3.3	6.8
4145	60	1.0	3.4	6.8	0.3	3.3	6.8
4133	18	3.2	4.6	37	0.3	2.5	20
4134	18	3.2	4.6	37	0.3	2.4	19
4148	18	3.2	3.4	27	0.3	1.2	10
4117	4000	0.5	0.5	16	0.3	0.3	10

Tabel 2.

The voltage with curve A response was obtained by carrying out the integration implied in equation (15). With the type A response the capacitance of the microphone have no influence on the noise, but this is the case when low frequencies are used. The noise pressures have been obtained by dividing, the noise voltage from the preamplifier, with microphone mounted, by the pressure sensitivity of the microphone.

It is apparent from table 2 that the most important noise source in an optimal sound detecting system is the microphone. The lowest sound pressure that may be measured depends on the magnitude of error which can be accepted. If a relatively large error can be tolerated the lowest sound pressure is the one where noise voltage is equal to the voltage from the sound pressure to be measured.

In this case the smallest sound pressure, that may be detected is 11 dB re $2 \cdot 10^{-4}$ dyn/cm^2 in the frequency range 20 – 20.000 Hz. If the signal has a much smaller bandwidth than 20 – 20.000 Hz it is possible to measure smaller sound pressures. The smallest mean square pressure spectral densities that may be measured with filters can be estimated from the figures 5, 6, 7 which display the noise spectra for the whole measuring system.

References:

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