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Ultra-low-noise preamplifier for condenser microphones

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The paper presents the design of a low-noise preamplifier dedicated for condenser measurement microphones used in high sensitivity applications, in which amplifier noise is the main factor limiting sensitivity of the measurements. In measurement microphone preamplifiers, the dominant source of noise at lower frequencies is the bias resistance of the input stage. In the presented solution, resistors were connected to the input stage by means of switches. The switches are opened during measurements, which disconnects the resistors from the input stage and results in noise reduction. Closing the switches allows for fast charging of the microphone capacitance. At low frequencies the noise of the designed preamplifier is a few times lower in comparison to similar, commercially available instruments. © *2010 American Institute of Physics*. [doi: 10.1063/1.3505110]

I. INTRODUCTION

High sensitivity measurements of acoustic signals are usually performed using condenser or electret microphones. In both cases the microphone is a capacitive transducer with relatively low capacitance, usually in the range from a few picofarads to a few tens of picofarads.[1] If the acoustic signal is weak, which is common, e.g., in photoacoustic applications, sensitivity of the measurements is often limited by noise of the detector and associated amplifier.[2–4] A comparison of the noise of a Brüel & Kjær measurement condenser microphone and amplifier is given in Fig. 1.[5] It is evident that at low frequencies, the noise of the preamplifier is dominant, which enables the sensitivity limit of the setup to be pushed further by improving noise properties of the amplifier. Such a low-noise circuit was the main objective of the work presented in this paper.

II. THEORETICAL BACKGROUND

Preamplifier circuits dedicated for externally polarized condenser microphones are commonly implemented in voltage amplifier configurations.[5,6] Example of such a circuit is given in Fig. 2. The high-ohmic resistance $R1$ supplies dc bias to the microphone, while the operating point of the amplifier $A1$ is set by another high-ohmic resistor $R2$ connected to the ground or another fixed potential. The resistance $R2$ is needed in order to provide a path for the input bias current of the active component $A1$ (operational amplifier or transistor). In the case of the circuit shown in Fig. 2 the main sources of noise are the resistors $R1$ and $R2$ and the active component $A1$. Comparison of thermal noise generated by the input stage resistance and the active component in a Brüel & Kjær condenser microphone preamplifier is given in Fig. 3.[5] It is clear that at low frequencies the noise properties of the preamplifier depend mainly on the thermal noise of the resistance, which is defined as

$$U = (4kTBR)^{1/2}, \tag{1}$$

where

U = noise voltage (rms) (V),
k = Boltzmann constant 1.38×10^{-23} (J/K),
T = absolute temperature (K),
B = bandwidth (Hz),
R = resistance (Ω).

In order to perform noise analysis it is convenient to present the circuit from Fig. 2 in the form given in Fig. 4(a). Taking into consideration that noise voltage increases with the resistance, it may seem at first that the best solution is to decrease $R1$ and $R2$ to such values so that the lower cutoff frequency of the amplifier (resulting from the time constant defined by the $R1$, $R2$, and Cm values) is equal or slightly below the lowest frequency used in the measurements. But it is evident that provided $C1 \gg Cm$, it is possible to transform the circuit from Fig. 4(a) to the equivalent circuit given in Fig. 4(b). Then it is clearly visible that the circuit composed by $R3$ (equivalent to the parallel connection of $R1$ and $R2$) and Cm acts as a high-pass filter with respect to the signal to be measured while it acts as a low-pass filter with respect to the noise generated by the resistance. And while the time constant of the mentioned low-pass filter is proportional to the resistance, the noise voltage increases with the square root of the resistance value. As a result, the noise properties of the amplifier should improve with the input resistance value (Fig. 5).[5] Therefore, if the pole frequency stays below the lower frequency we are interested in, it is convenient to have $R3$ as large as possible. And that is why typical input resistance values of condenser microphone preamplifiers are at the level of 10–50 GΩ.[5] Higher values are not practical, as resistances $R1$ and $R2$ influence not only the lower cutoff frequency of the amplifier but they also limit speed of charging the microphone and separating capacitance $C1$ to the polarization voltage after powering up the amplifier.[5] For example, if $R1 = R2 = 20$ GΩ, $Cm \approx 15$–20 pF (typical capacity of a 1/2″ condenser microphone), and $C1 = 1$ nF, the time constant that is relevant, in this case, is $(R1 + R2)*C1 \approx 40$ s and increases with $R1$ and $R2$.

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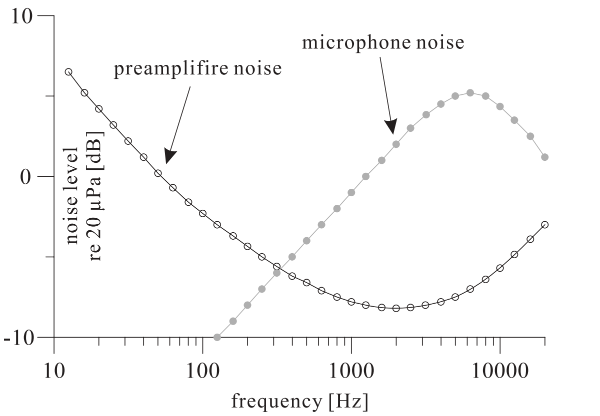

FIG. 1. Comparison of the noise of a Brüel & Kjær measurement condenser microphone and amplifier (Ref. 5).

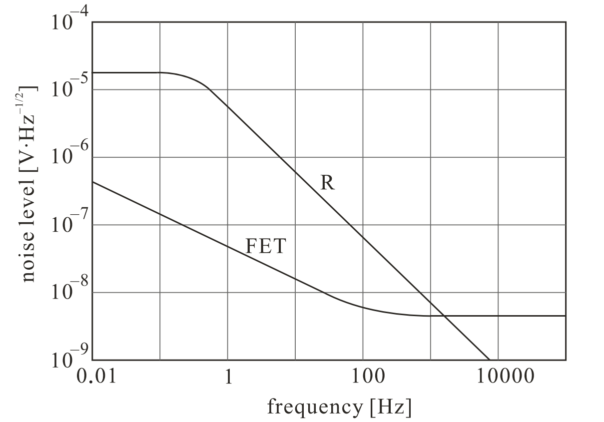

FIG. 3. Comparison of thermal noise generated by the input bias resistors and the active component in a Brüel & Kjær condenser microphone preamplifier (Ref. 5).

III. CIRCUIT DESIGN

The problem described above was solved in a circuit shown in Fig. 6. Both switches $K1$ and $K2$ are normally (if the relay containing $K1$ and $K2$ is not driven) closed. As a result both capacitances (Cm and $C1$) are quickly charged after power-on of the preamplifier and discharged when the power is removed. $R3$ and $R4$ are used in order to limit charge currents to safe values. The switches are opened only for the time of measurements. Then the input resistance results from leakage currents only and is at the level of teraohms. Since the equivalent input resistance is in the order of teraohms, for the reasons discussed before, the noise induced by such an equivalent resistance is negligible with respect to the noise introduced by the equivalent input noise sources of the amplifier. With the both switches opened, the charge on the microphone capacitance changes slowly due to leakage currents but careful assembly and appropriate selection of components can easily reduce the leakage currents below picoampere. For a $1/2''$ measuring condenser microphone it is possible to obtain change of the microphone dc voltage (resulting from the mentioned leakage) with a speed of less than 1 mV/s. This means that during 1 min measurement, a microphone voltage of 200 V will change by not more than 60 mV, which corresponds to an error of 0.03%, which is acceptable in most applications. A similar situation occurs at the amplifier input $A1$, where (except from the leakage currents) the input bias current of the amplifier must be also taken into account. For this reason the amplifier should be selected not only with the lowest possible noise figures but also with the lowest possible bias currents. Fortunately, it is possible to find operational amplifiers with typical bias currents of just a few femtoamperes (at room temperature) and a relatively low level of voltage and current noise—e.g., LMC662 from National Semiconductor.[7] Selection of all the other components of the input stage of the amplifier and proper assembling—aimed at minimum leakage currents—is critical. For this reason the use of semiconductor switches is not recommended. In the test circuit, subminiature (5.2 × 6.5 × 10 mm) G6K relay (Omron) was used (Fig. 7), and the components of the input stage were up-in-the-air wired. Capacitor $C1$ cuts off polarization voltage of +200 V from input of the amplifier $A1$. In order to lower the leakage, a styroflex $C1$ capacitor rated for 1000 V was used. As a result of low leakage currents obtained in the tested circuit, a single initial charge-up of the microphone was enough for continuous operation of over an hour with the gain error below 2%. (The tests were performed at the room temperature.) Operation of $K1$ and $K2$ requires special attention because if the switches are controlled improperly, the circuit can be damaged. It should be noticed that such damage may occur if a voltage step arriving at the noninverting input of the $A1$ operational amplifier and resulting from closing the switches has sufficient amplitude to bring the

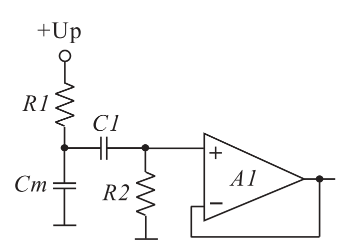

FIG. 2. Input stage of a voltage amplifier dedicated for condenser microphones.

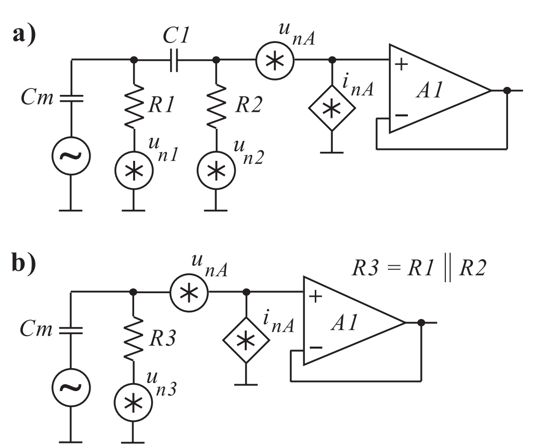

FIG. 4. Circuit diagrams used for noise analysis of the input stage of the preamplifier from Fig. 2: (a) basic circuit diagram, (b) simplified circuit diagram.

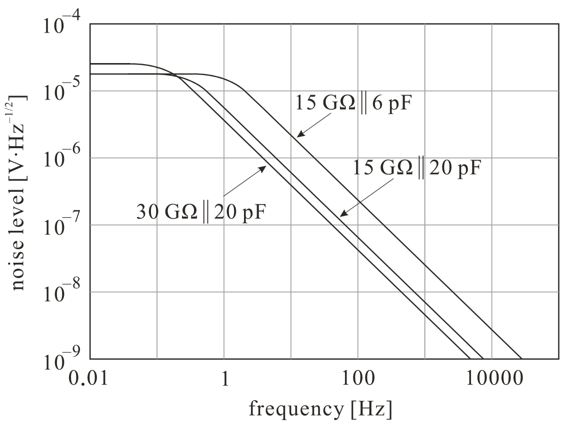

FIG. 5. Influence of the input resistance on the noise properties of the preamplifier (Ref. 5).

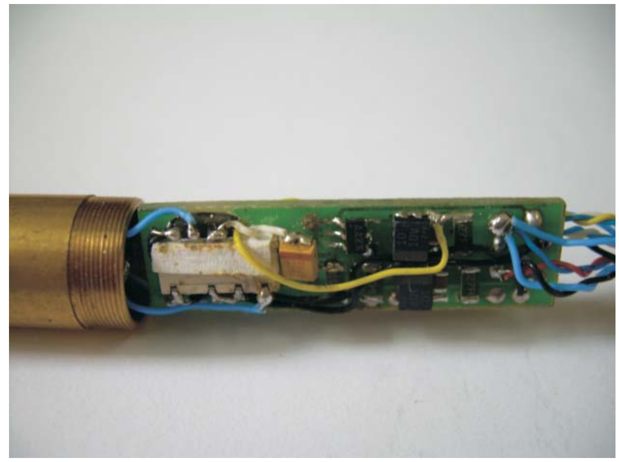

FIG. 7. (Color online) The designed preamplifier fitted to a 1/2 in. brass cartridge. The switches, LMC662, and some other components of the input circuit are air wired.

potential of the mentioned noninverting input out of the power supply rails of the LMC662. That is why both switches should be normally closed. In particular they should remain closed during powering the preamplifier on or off. In this way the capacitances Cm and $C1$ are smoothly charged and discharged. Such an approach is also needed in the instance where the switches are not rated to withstand high dc voltages across their terminals, so it is important to keep the potential difference between the ends of every switch limited. The switches should be opened only when the preamplifier is used for measurements. Moreover, every few minutes (if the measurements are longer) the switches should be closed again for a short time (e.g., 1 s) in order to recharge the capacitances. If a single measurement does not last very long (i.e., is limited to the mentioned few minutes), the voltage drop resulting from the leakage is relatively small (should not exceed a fraction of volt). Even though closing the switches will result in a voltage step at the LMC662 noninverting input, it will not harm the operational amplifier, as the signal will be within the power supply rails of the LMC662.

Amplifier $A1$ is used in a voltage follower configuration. As a result the signal from the microphone is passed through the $C1$ capacitor and obtained at the $A1$ output, which acts as a low-resistance signal source. $C2$ and $R3$ form a high-pass filter and set the lower corner frequency of the whole preamplifier circuit. $R3$ allows also for a bias current to flow to the

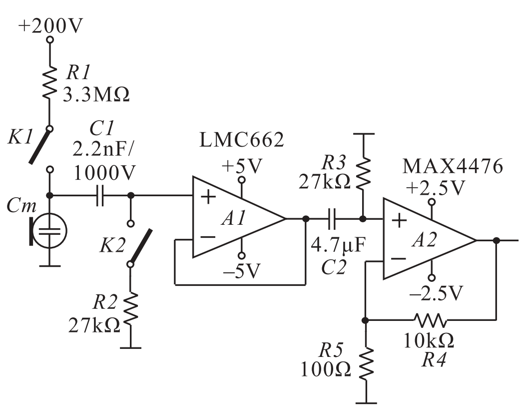

FIG. 6. Circuit diagram of the designed preamplifier.

noninverting input of the $A2$ operational amplifier. Selection of the $A2$ amplifier was based mainly on its noise properties. Amplifiers $A1$ and $A2$ can be treated as uncorrelated noise sources, with the resulting voltage noise density,

$$e_{n\_\mathrm{total}} = \left(e_{n\_A1}{}^2 + e_{n\_A2}{}^2\right)^{1/2}. \tag{2}$$

It was assumed that presence of $A2$ amplifier should increase the total noise density e_{n_total} by no more than 10%. Hence, the voltage noise density of $A2$ e_{n_A2} must have been less than 20% of e_{n_A1}. As $A2$ amplifier input is connected to a low-resistance signal source, the current noise value of this amplifier was less critical. The MAX4476 used in the tested preamplifier fulfills the mentioned voltage noise density criterion, has also very low current noise density, and has very low level of distortions. But it should be mentioned that many other operational amplifiers can be used instead of MAX4476; e.g., AD8675 has even lower voltage noise density, has excellent power supply rejection ratio (PSRR), and can be powered from the same ±5 V as LMC662.

The preamplifier gain K depends on the ratio of $R4$ and $R5$:

$$K = 1 + R4/R5. \tag{3}$$

Obviously, the use of low-noise supply voltages and careful decoupling of all the supply pins of both amplifiers are critical.

IV. MEASUREMENTS AND DISCUSSION

The measured noise of the preamplifier and its theoretical noise characteristics are given in Fig. 8 and show good agreement, which supports the notion that the noise of the designed circuit depends mainly on the operational amplifier noise properties. The data are plotted in the form of the 1/3-noise spectra for direct comparison to noise characteristics of commercial condenser microphones and preamplifiers, which are commonly presented in such a form. Theoretical calculations were based on the noise circuit of the first stage of the preamplifier (Fig. 4), and typical voltage noise characteristics of

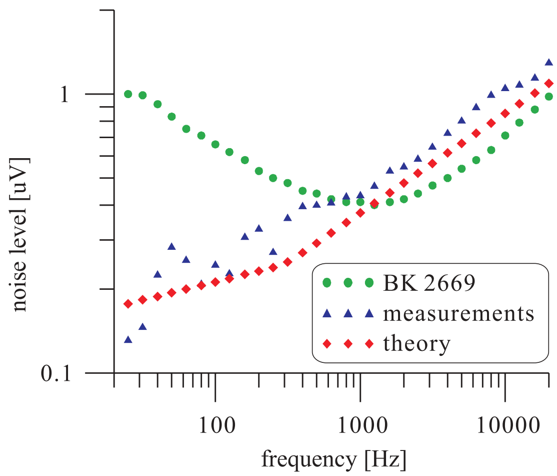

FIG. 8. (Color online) 1/3-octave theoretical and measured noise spectrum of the designed preamplifier compared with BK2669 characteristics.

LMC662 were given in the device datasheet.[7] Further stages of the amplifier were not taken into account, as MAX4476 and following circuits have relatively low influence on the noise properties of the whole preamplifier—roughly estimated as approximately 10% of the total noise. The theoretical values are slightly lower than the measured ones, but it should be noted that the calculations have not included precise current noise evaluation. (Datasheet of LMC662 does not contain characteristics of the current noise—the only available data are typical value of this noise at the frequency of 1 kHz). Also noise properties of the particular LMC662 used in the test circuit could have been slightly worse than typical numbers given in the datasheet. Nevertheless, a comparison of the measured noise characteristics of the designed and tested circuit with a similar Brüel & Kjær preamplifier[8] shows clearly that at low frequencies the solution presented in this paper has much better noise properties than the commercial one. It should be also noticed that vertical axis of the chart in Fig. 8 is logarithmic and for higher frequencies (at which, as already stated, the microphone noise is dominant), noise of the designed circuit is only approximately 30% higher than that of the Brüel & Kjær preamplifier while at low frequencies the difference is a few hundred percent in favor of the solution shown in Fig. 6.

V. CONCLUSIONS

Presented design of a preamplifier dedicated for condenser measurement microphones was optimized toward ultrasensitive acoustic measurements which are limited by the noise properties of the microphone and associated amplifier, for example, in such applications as photoacoustic measurements. The proposed solution has advantages of a very high input resistance and fast charging to the polarization voltage. At lower frequencies the achieved noise levels of the presented circuit are a few times lower than those offered by commercial solutions of such microphone preamplifiers.

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