NOTES

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Electrical performance of a liquid helium-cooled transformer*

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The noise performance of an audio-frequency transformer cooled in liquid helium and combined with a low-noise amplifier is reported. It is found that the transformer, modified for operation at low temperatures, behaves nearly as a noiseless transformer for low source impedances. The minimum noise temperature of the transformer–amplifier combination is 1.8 K for a 3 Ω source resistance. The bandwidth of the cooled transformer is similar to that obtained at room temperature.

Many recently developed superconducting transducers, such as quantum interference devices and bolometers, have low source impedances, frequently in the range of 1–10 Ω. In many cases, the useful sensitivity of these transducers is limited by the noise introduced by the amplifier which processes the output signal. Some low-noise room-temperature amplifiers do have noise temperatures in the liquid helium temperature range, but such performance is available only for high (≈ 1 MΩ) source impedances. To obtain this low-noise performance for low source impedances, transformers must be used to shift the amplifier's low-noise region to lower impedances.[1] Room-temperature transformers, however, contribute significant noise when used with cooled sources, due to the room-temperature thermal (Johnson) noise of their winding resistance. Cooled transformers have been used to minimize this problem, although details of their performance have not been widely reported. To guide the experimenter contemplating such an application, this Note reports the bandwidth and noise temperatures achievable with a commercial transformer specially modified for operation in liquid helium.

The noise temperature T_N is a convenient characterization of the noise added to source Johnson noise by the transformer–amplifier combination. As usually defined,[1]

$$4k(T_s+T_N)R_s\Delta f=(V_{No}/G)^2,$$

where $k=1.38\times10^{-23}$ J/K is Boltzmann's constant, T_s is the temperature of the source resistance R_s, Δf is the noise bandwidth, V_{No} is the rms noise voltage at the amplifier output, and G is the voltage gain of the transformer–amplifier combination. If T_N is less than T_s, the noise from the source dominates, and improvement of the transformer–amplifier combination is usually not necessary.

Since low-impedance sources are of principal interest, a commercially available transformer with the maximum available turns ratio was selected, the Triad G-4 wired for a turns ratio of 1:350. Ideally, impedances will be transformed by approximately 10^5 by this transformer. The amplifier, a Princeton Applied Research (PAR) model 185, had a measured input noise voltage of 3.2×10^{-9} V/(Hz)^{½} at 500 Hz and a stated input noise current of approximately 4×10^{-15} A/(Hz)^{½} at 500 Hz. The amplifier's minimum noise temperature is 0.5 K for a 800 kΩ source resistance. Source resistors used in the measurements were metal film or wire-wound types, and were at the same temperature as the transformer for convenience. A PAR 124 served as the narrowband detector of output noise voltage, with the noise bandwidth calibrated by means of a room-temperature resistor connected to the input of the PAR 185. All low temperature tests were carried out with the transformer in a helium Dewar equipped with high permeability magnetic shielding.

The unmodified transformer presented two problems when used in liquid helium: during the first warming, the hermetically sealed can popped open explosively due to rapid expansion of helium which had leaked inside, and for all runs, cracking-like electrical transients were observed on the oscilloscope output monitor. These problems were eliminated by removing the transformer's external shields and the wax-like filler. A closed superconducting lead shield was then substituted, and with this modification, the G-4 transformer was found to be quite suitable for reliable low temperature service. Thermal cycling had no noticeable effect. Also, vibration encountered under normal experimental conditions had no effect, although banging directly on the Dewar did produce output transients. Lastly, pickup at 60 Hz by the transformer alone was barely perceptible, about 10^{-11} V rms referred to the transformer input.

Results for the transformer gain are shown in Fig. 1. As is evident from the figure, cooling the transformer does not greatly reduce the bandwidth. The small reduction at low frequencies is due to a 50% decrease of the transformer's

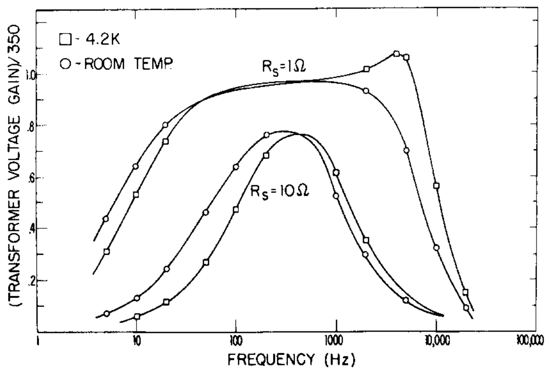

FIG. 1. Normalized transformer voltage gain as a function of frequency for the transformer at 4.2 K, □, and at room temperature, ○, for source resistances of 1 and 10 Ω.

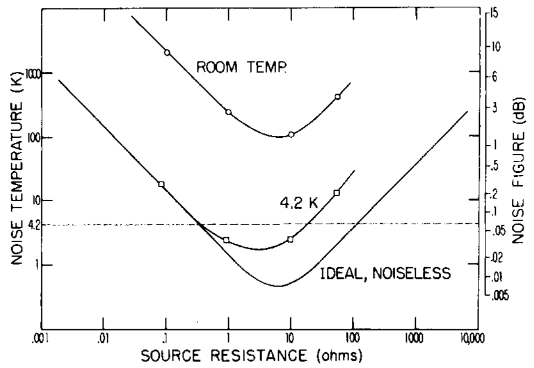

FIG. 2. Noise temperature at 500 Hz of the Triad G-4 transformer combined with a PAR 185 amplifier, measured with the transformer at 4.2 K, □, and at room temperature, ○, and calculated for the 185 with an ideal noiseless transformer having the same turns ratio as the G-4. Noise figures are for a source temperature of 290 K, the usual convention, and are defined as N.F. $=10\log[1+(T_N/290)]$.

self-inductance upon cooling. With large R_s, the over-all bandwidth is substantially reduced at either temperature.

Results for the measured noise temperature of the combined G-4 transformer and 185 amplifier are shown in Fig. 2 for the transformer at room temperature and at 4.2 K. The calculated noise temperature assuming use of an ideal noiseless transformer is also shown for comparison. All measurements were made at 500 Hz, roughly midband. The calculated noise temperature for the ideal noiseless transformer is determined by the noise of the 185 amplifier exclusively, with the resistance scale set by the impedance transformation of approximately 10^5 of the ideal transformer.[1] As seen in the figure, the cooled transformer performs essentially as an ideal noiseless transformer for R_s less than 0.5 Ω, adding no significant noise of its own. Noise referred to the transformer input is 10^{-11} V/(Hz)$^{\frac{1}{2}}$. For intermediate R_s, 0.5 Ω–20 Ω, the Johnson noise of the 4.2 K source dominates, and T_N is less than 4.2 K. For increasing R_s, the noise temperature rises in both the actual and the ideal case, due to the increasing contribution of current noise of the amplifier input. Actual performance of the cooled transformer is less than ideal, however, because the transformer's gain is reduced below the ideal 350. For a 1 Ω source, close to optimum, T_N is less than 4.2 K from about 50 Hz–10 kHz. These general statements would also apply for a lower turns ratio, $1:n$, but all resistances described above would be larger by approximately $(350/n)^2$. As is evident from the figure, the noise performance at room temperature is considerably poorer. Winding resistance at room temperature is 0.7 Ω referred to the primary, and this sets the minimum T_N. At 4.2 K, the winding resistance is 0.01 Ω.

In summary, the Triad G-4 transformer, modified for use in liquid helium, works extremely well, and combined with a good low-noise amplifier should be well suited to low-noise amplification from low-impedance low-temperature sources.

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[1]S. Letzter and N. Webster, IEEE Spectrum 7, No. 8, 67 (1970).

Three-terminal shielded resistors for fast electrometers*

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The design of electrometer feedback resistors for use at frequencies up to the kilohertz range is discussed. It is shown experimentally that the addition of capacitive coupling between the electrometer output and the center of the feedback resistor, combined with suitable shielding, gives substantially better performance at high frequencies than is obtainable with more conventional designs.

Resistors in the range 10^8–10^{13} Ω are frequently used in electrometer feedback circuits when small currents are to be measured. If the currents are both small and rapidly varying, the effects of the stray capacitances associated with these resistors must be considered.

The effects of stray capacitance between the electrometer input and ground, and between the input and output portions of the electronic circuitry, are quite well understood. They are minimized by suitable physical design of the input wiring, by the use of large negative amplifier