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Practical Realization of Johnson's Noise Thermometer

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Summary: A practical realization of a thermometer utilizing Johnson's noise is presented. At 2019 new definition of SI units was adopted an Kelvin is not based on triple point of water as it used to be before. Boltzmann constant has a fixed value instead from which Kelvin could be derived in various ways.

Keywords: Johnson's noise thermometry, thermal noise, correlation, amplifier noise, electromagnetic interference, liquid nitrogen temperature

Introduction

The goal of the project was to construct a two-channel noise thermometer. This is a thermometer that must be calibrated using a single temperature point (e.g., the triple point of water), and thereafter, it is capable of measuring any other temperature. The range is limited only by the thermal endurance of the materials used, which can easily be selected so that the thermometer operates reliably from any cryogenic temperatures up to approximately 200 ℃ or even higher.

The temperature measurement is uniquely determined by fundamental physical principles, and thus any temperature point can be verified, which makes the noise thermometer well-suited for use in metrology.

The basic phenomenon utilized is the thermal noise of a resistor, which was first described in 1926 by John B. Johnson and further clarified in 1928 by Harry Nyquist. Ignoring the details, we can say that the principle is quite simple and easily applicable.

From the described properties, it might seem that the noise thermometer has excellent characteristics, its principle has been known for nearly a hundred years, and one might expect it to be widely adopted. However, the opposite is true. The noise thermometer is rarely used, almost exclusively in specialized applications—such as measuring the Boltzmann constant. In industrial practice, noise thermometers are a rare exception, found only in certain cryogenic temperature measurements.

The reason for the limited use of noise thermometers could be their slow response time, which is their main disadvantage. In principle, measurements need to be taken over an extended period to gather enough data. The uncertainty in the measured temperature depends on the measurement time, so measuring a single temperature can take several hours, which is a significant barrier for industrial applications. However, in metrology, long measurement times are quite common.

A noise thermometer is primarily an extremely sensitive device that cannot function properly if exposed to external electromagnetic interference. The measured values are so small that the main challenge in its implementation is designing the best possible shielding. As demonstrated during the research, mechanical vibrations are also highly detrimental.

Theory

A noise thermometer measures temperature based on the fact that the voltage noise of a resistor is proportional to the thermodynamic temperature T. Specifically, the average power on a resistor, resulting from the chaotic motion of electrons, can be expressed as:

$$P = 4kT\Delta f$$

where Δf is the bandwidth, and k is the Boltzmann constant, $k = 1.380649 \times 10^{-23}$ J/K. Electrical power can be expressed using the resistance R and voltage U, with $P = U^2/R$, which, together with the previous equation, leads to

$$U_{\text{eff}} = \sqrt{4kTR\Delta f}$$

where U_{eff} is the effective value of the resistor's noise voltage.

For a resistor of 1 kΩ at a room temperature of around 300 K, and a measuring device operating with a bandwidth of 125 kHz, the effective noise voltage is approximately 1.29 microvolts. This voltage, after amplification, is supplied to the input of a measuring card with a range of ± 5 V. The amplifier gain should be such that the measuring range is optimally utilized without exceeding limit values. The peak value is significantly higher than the effective value. Assuming a factor of ten, this results in an exceedance in a statistically negligible number of cases. Then,

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the amplifier gain is calculated as $A = 387597$. If we require measurements at higher temperatures than 300 K, the gain must be lower.

Two channel measurement

Every amplifier is a source of noise, which adds to the resistor's noise. In further processing, it is no longer possible to distinguish the level of noise produced solely by the resistor. Therefore, a dual-channel variant was assembled, allowing the resistor noise to be measured independently of the amplifiers, using two independent amplifiers. The principle relies on the fact that amplifier noises are completely independent, while the resistor noise affects both amplifiers simultaneously. It can be proven that the product of both channels has a mean value proportional only to the resistor noise. Based on this principle, a correlator (see Fig. 1) was programmed to calculate the mean value of the product of both channels, process blocks of digitized data, and output a value theoretically proportional to the thermodynamic temperature. Using two channels offers significant advantages. Not only is the correlator's response linear with respect to the resistor's temperature, but the line also starts from zero. Therefore, only a single temperature point is needed to calibrate the entire setup. Moreover, the temperature of the amplifiers does not need to be controlled, as their noise — dependent on the electronics' temperature — cancels out.

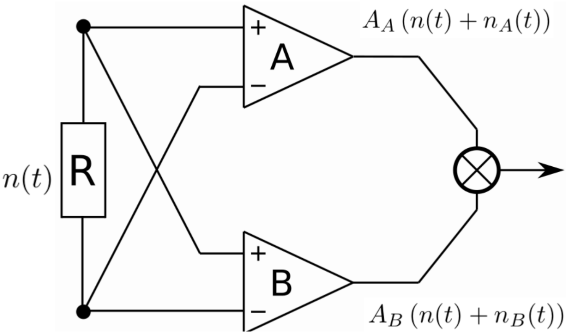

Fig. 1: A correlator made of two independent amplifiers

Results

The setup needs to be calibrated using one fixed temperature point. For this purpose an ice bath has been used to get proportionality constant. Afted this step the sensing resistor was immersed in liquid nitrogen with table value of temperature $-195.8°$ C. The response of the thermometer was monitored and the lowest measured stable value was 180 mK lower than the correct value, see Fig. 2.

Fig. 2: The time dependence of the measured temperature of liquid nitrogen shows a stable minimum temperature of $-195.98°$ C.

References

[1] Johnson, J. (1928). "Thermal Agitation of Electricity in Conductors". Physical Review. 32 (97): 97–109

[2] Nyquist, H. (1928). "Thermal Agitation of Electric Charge in Conductors". Physical Review. 32 (110): 110–113.

[3] Fischer, J; Fellmuth, B; Gaiser, C; Zandt, T; Pitre, L; Sparasci, F; Plimmer, M D; de Podesta, M; Underwood, R; Sutton, G; Machin, G; Gavioso, R M; Ripa, D Madonna; Steur, P P M; Qu, J (2018). "The Boltzmann project". Metrologia. 55 (2)

Conclusion

A practical implementation of a Johnson noise thermometer has been presented. Despite significant challenges related to shielding and overall noise immunity, results surpassing those of industry-standard Class AA platinum thermometers (Pt-100) have been achieved. Not only is the uncertainty lower across most temperature ranges, but the main advantage is that the thermometer's principle is derived directly from the Boltzmann constant, aligning with the redefined Kelvin in the SI system since 2019.

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