Continuous Resistance Temperature Detector Calibration Using Johnson Noise Thermometry

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Abstract

Johnson noise thermometry (JNT) is approaching a state of technological development to where it may be practically applied to continuous recalibration of resistance temperature detectors (RTDs) in industrial process environments. Johnson noise arises from the motion of the electrons and protons in a resistor as they thermally vibrate. Fundamentally, temperature is merely a convenient representation of the mean translational kinetic energy of an atomic ensemble. Since Johnson noise is a fundamental representation of temperature (rather than a response to temperature such as electrical resistance or thermoelectric potential), Johnson noise is immune from chemical and mechanical changes in the material properties of the sensor. As such, on-line measurement of the Johnson noise of the resistive element may be used to continuously recalibrate the RTD resistance-to-temperature relationship effectively eliminating the requirement for periodic recalibration. Johnson noise, however, is fundamentally a small signal ($\sim 4x10^{-7}\ V_{rms}$ *for a 100 Ω resistor at 300 K, using a 100 kHz bandwidth) spread throughout the frequency spectrum. Creating the electronics and signal processing algorithms required to effectively measure and interpret the noise signal remains challenging. Oak Ridge National Laboratory has recently developed JNT electronics and signal processing technology under a U.S. Department of Energy International Nuclear Energy Research Initiative Project with the Korean Atomic Energy Research Institute. Measuring the RTD resistance continuously and quasi-continuously making corrections to the RTD resistance-to-temperature relationship is central to the new JNT implementation. The new JNT implementation incorporates amplifier design concepts from previous JNT developments while employing modern digital signal processing technology to remove spurious signals from the measured noise spectrum.*

1. INTRODUCTION

The primary benefit of Johnson noise thermometry is its lack of need for recalibration. Johnson noise is a first-principles representation of temperature. Fundamentally, temperature is merely a convenient representation of the mean kinetic energy of an atomic ensemble. Since Johnson noise is a fundamental representation of temperature rather than a response to temperature such as electrical resistance or thermoelectric potential, Johnson noise is immune from chemical and mechanical changes in the material properties of the sensor. Johnson noise thermometry has been applied to in-core temperature measurement for more than thirty years now [1] and more generally Johnson noise has been used for temperature measurement for more than fifty years [2]. Further Johnson noise thermometry has been employed repeatedly in operating nuclear power plants in the USA [3, 4], Germany [5], and Japan [6].

Several limitations to JNT technology, however, have prevented its widespread adoption into the nuclear power industry. The first of these is change in the transmitted noise by the signal cables connecting the sensor to the measurement electronics. The cable's capacitance reduces the high frequency portion of the sensor noise before it reaches the measurement system. Further, under the aggressive temperature and radiation environments of a nuclear power plant, the cable capacitance will change over time changing the amount of noise signal transmitted. Two other technological challenges to deployment of JNT are electromagnetic interference spikes and microphonics. Johnson noise is fundamentally a small signal and without great care in the installation, these other noise sources can dominate the measured noise. Finally, the long-term drift in the required high-gain measurement electronics can defeat the rationale for employing an ab initio based measurement technique. The purpose of the current I-NERI JNT project is to develop a working JNT system that overcomes each of these limitations and whose techniques are suitable for application at a nuclear power plant for primary loop temperature measurement.

2. JOHNSON NOISE THERMOMETRY BACKGROUND

The Nyquist equation describes the voltage produced by the vibration of the electrons within a resistor at a given temperature. For frequencies below a few gigahertz, Equation (1) shows the relationship between the absolute temperature of a resistor (T), its resistance (R), the frequency band of measurement Δf, and the measured mean-square noise voltage $\overline{V^2}$.

$$\overline{V^2} = 4k_B TR\Delta f \qquad (1)$$

where k_B represents Boltsmann's constant ($1.38\text{x}10^{-23}$ joules/Kelvin).

A direct measurement of the Johnson noise for temperature measurement has several challenges. First, the amplifier gain needs to be both known and stable. Second the amplifier passband and filtering effects of connection cabling must be well known to within the required measurement accuracy. Finally, the resistance of the sensor must be independently and accurately measured. To avoid these difficulties, early Johnson noise thermometers performed a ratio of two noise voltage measurements, one with a resistor at the measurement temperature and the other at a known temperature, switched onto a single amplifier channel. However, changing the connection of the sensor to the high-gain measurement circuit introduced noise and decreased reliability.

The approach that ORNL staff took to minimize these difficulties during the mid-1980s was to follow the work of Pepper and Brown [7] in which a resistive sensor is connected in series with an inductor and a capacitor forming a tuned circuit. In this approach the ideal mean squared noise voltage is given by

$$\overline{V^2} = \frac{k_B T}{C} \qquad (2)$$

where C is the capacitance of the capacitor. The major advantage of this technique is that, for lossless inductors and capacitors (provided that the measurement bandwidth is greater than the tuned circuit bandpass), the measured voltage output is independent of the sensor resistance and the inductance. No measurement of the sensor resistance is needed. Another advantage of the technique is that for a properly tuned circuit, most of the signal power lies in a relatively small band near the resonant frequency. This allows the amplifier bandwidth to be relatively small and reduces its noise contribution to the measurement uncertainty. A practical limitation with this approach, however, is loss in the inductors. Real inductors have winding resistances (typically frequency dependent) that dissipate energy. In practice, this limits the overall accuracy obtainable with a tuned circuit implementation of Johnson noise thermometry.

Another implementation restriction for Johnson noise thermometry in nuclear power reactors is the capacitive effect of the cable connecting the sensing resistor to the first stage amplifiers. If the cable has significant capacitance, it will block the high frequency portion of the sensor noise before it reaches the measurement system. This filtering of the upper frequencies reduces the bandwidth of the Johnson noise signal. Under the high temperature and radiation environment of power reactors, the cable capacitance will change over time. One way of compensating for the cable effect is to periodically measure its input impedance and calculate its transfer function. However, the best technique remains to locate the first-stage amplifier near the sensor. Some of the previous work with JNT at nuclear power was restricted to making measurements at the control room ends of the RTD cables. This was a significant limitation to the achievable system accuracy.

Two additional JNT signal-processing concepts were investigated by ORNL in the late 1980s and early 1990s. In the first of these, the temperature measurement resistor is connected in parallel to two separate high input impedance amplifiers. The output of these amplifiers is partially correlated since each consists of the sum of a correlated noise voltage and uncorrelated amplifier noise voltage. If two Johnson noise amplifier signals, connected to the same resistance, are combined and time averaged, the correlated part of the noise will persist, but the uncorrelated amplifier noise will approach zero. Figure 1 illustrates the concept of cross-correlation; the measured voltage from one amplifier channel is Fourier transformed and correlated and with that from the other to form a cross power spectral density (CPSD) effectively eliminating the noise contribution from the amplifier electronics.

Johnson noise has a flat (white) spectral energy distribution. The shape of the power spectral density functions displayed in Figure 1 is a result of the combined effects of filtering out both the low and high frequencies from the noise and the frequency dependent gain of the amplifier circuit. The low frequency filtering is applied to eliminate the non-thermal noise generated by mechanical vibrations. These microphonic signals are limited to less than a few tens of kilohertz. The upper frequency filtering is applied both to avoid aliasing higher frequencies into the measurement band as well as to minimize the impact of sensor-to-amplifier cable capacitance induced restriction of high frequency transmission.

The CPSD function has units of volts squared per hertz and expresses the voltage-squared content per unit frequency of the measured voltage signal. Integrating the CPSD function over frequency and averaging the result over time provides the mean-square noise voltage for the Nyquist equation.

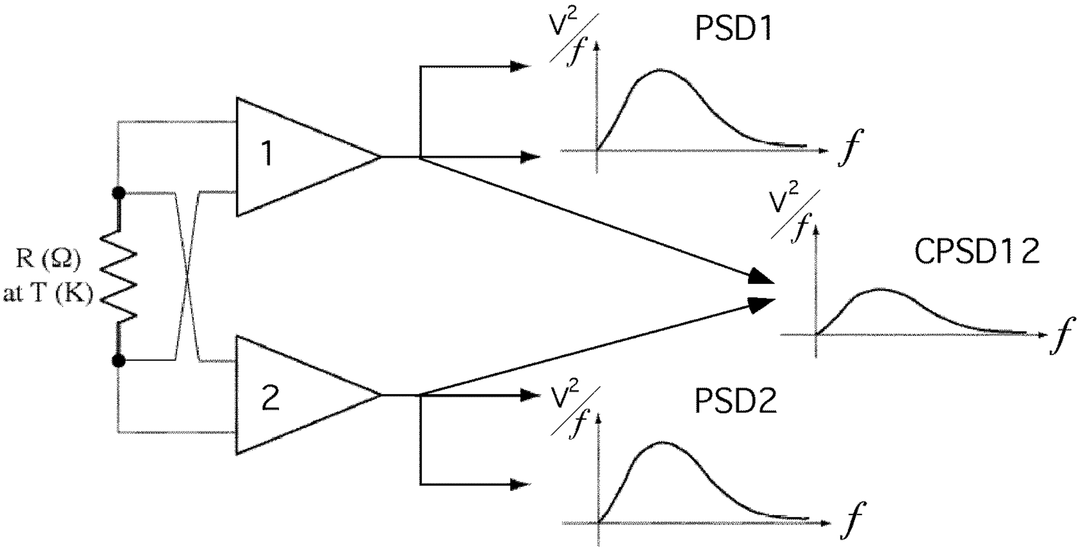

Figure 1. Power Spectral Density Function (PSD) of Each Amplifier Channel Containing Both Correlated and Uncorrelated Noise and the CPSD Function From Both Amplifiers Containing Only Correlated Noise.

Electromagnetic interference spikes and microphonics are two of the biggest problems for a practical implementation of Johnson noise thermometry. In many situations, these effects can completely dominate the noise measurement. This puts a premium on well-implemented grounding, shielding, and filtering. A complementary technique to reduce these effects is to use both knowledge of the spectral energy content of Johnson noise and digital signal processing to recognize and eliminate interferences. Typically narrowband electromagnetic interference appears as spikes in the long-term average CPSD that can be recognized and removed with only a small reduction in measurement bandwidth as illustrated in Figure 2.

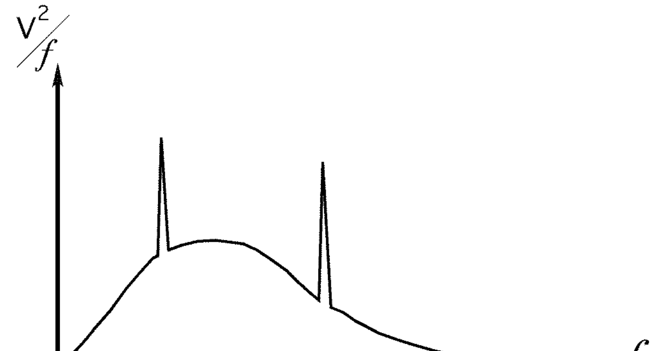

Figure 2. CPSD With Narrowband EMI Spikes.

3. I-NERI JNT IMPLEMENTATION

The measurement system architecture developed under the current I-NERI project provides for continuous calibration throughout the life of the instrument. The system consists of two major subsystems: (1) instrument head and (2) receiver and signal processing—shown in Figure 3. The instrument head portion contains analog amplifier components that, although not implemented in a radiation tolerant form during the current project, can be implemented to perform under challenging radiation environments. The receiver and signal processing subsystem, which contains both analog and digital electronic components, can be located remotely from the head in a non-containment zone. Interconnection between the two subsystems is made by a bundle of shielded cables that can extend their separation to 300 meters.

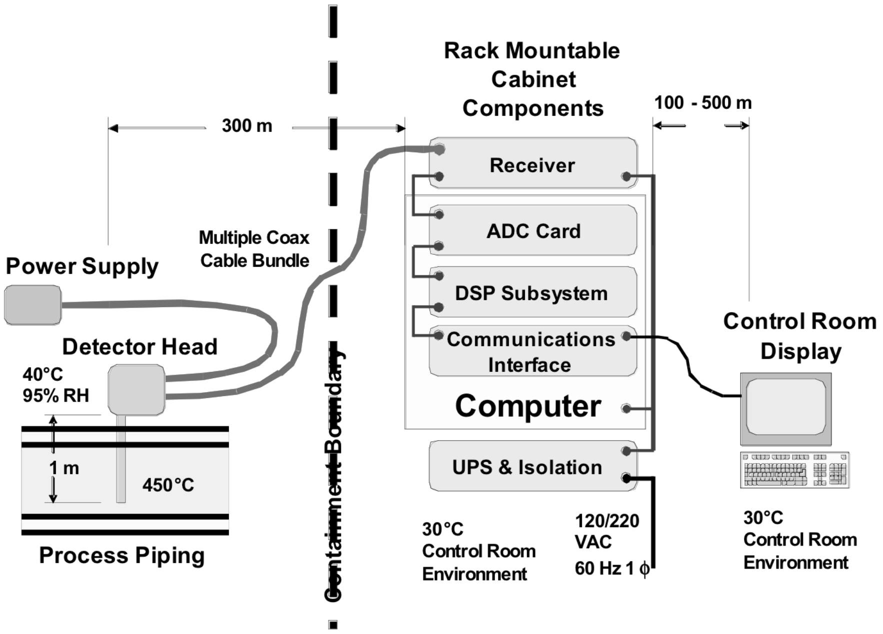

Figure 3. Plant Layout of JNT System

While the underlying concepts (under NASA sponsorship) and a laboratory prototype (under EPRI sponsorship) of both the cross correlation and digital signal processing had previously been developed by ORNL and the University of Tennessee, the high speed digital signal processing required remained prohibitively expensive in the early 1990s. Consequently, the cross-correlation amplifier electronics were never implemented in an integrated form, and the signal processing software was never finalized.

The current International Nuclear Energy Research Project, led by ORNL on the U.S. side and with the Korean Atomic Energy Research Institute leading the Korean JNT tasks, is focused on implementing a dual mode resistance and Johnson noise thermometer in a rugged, integrated, prototype form. The resistance measurement serves the dual purpose of providing the necessary impedance measurement for the Nyquist equation as well as providing a prompt temperature measurement much as in a traditional RTD based temperature channel. Since Johnson noise is a stochastic process, some time is required to perform a measurement. The temperature measurement in the dual mode thermometer is therefore made as a simple resistance measurement whose resistance to temperature conversion is quasi continuously updated using Johnson noise. A schematic illustrating the measurement process is shown as Figure 4.

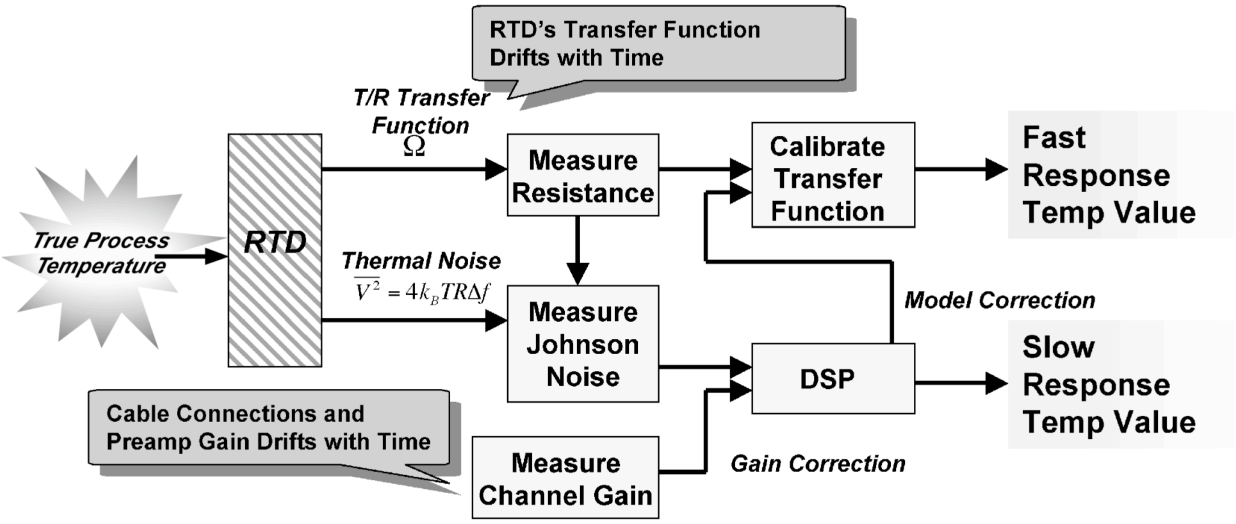

Figure 4. Johnson Noise Thermometry Measurement Process Schematic.

The CPSD provides the mean-square noise voltage, and the resistance is independently measured, so the remaining variables that have to be known to obtain temperature from the voltage measurements are the amplifier gain as a function of frequency and the effective measurement frequency band (Δf). The technique currently used to obtain the gain-bandwidth product is to initially calibrate the measurement using a known temperature and treating both properties thereafter as a single constant.

A layout of the developed system is shown in Figure 5. High-gain, wide-band Johnson noise preamplifiers with a precision resistance bridge have been implemented in high-density, discrete component electronics. A continuous amplifier gain calibration scheme has also been implemented. The digital signal processing logic has been implemented in LabVIEW™ on a desktop computer and is in the process of being implemented in a field programmable gate array (FPGA) and dedicated digital signal processing (DSP) chip format. The preamplifier head and resistance probe have been packaged in a shielded aluminum enclosure and a twisted pair signal interconnection scheme has been implemented.

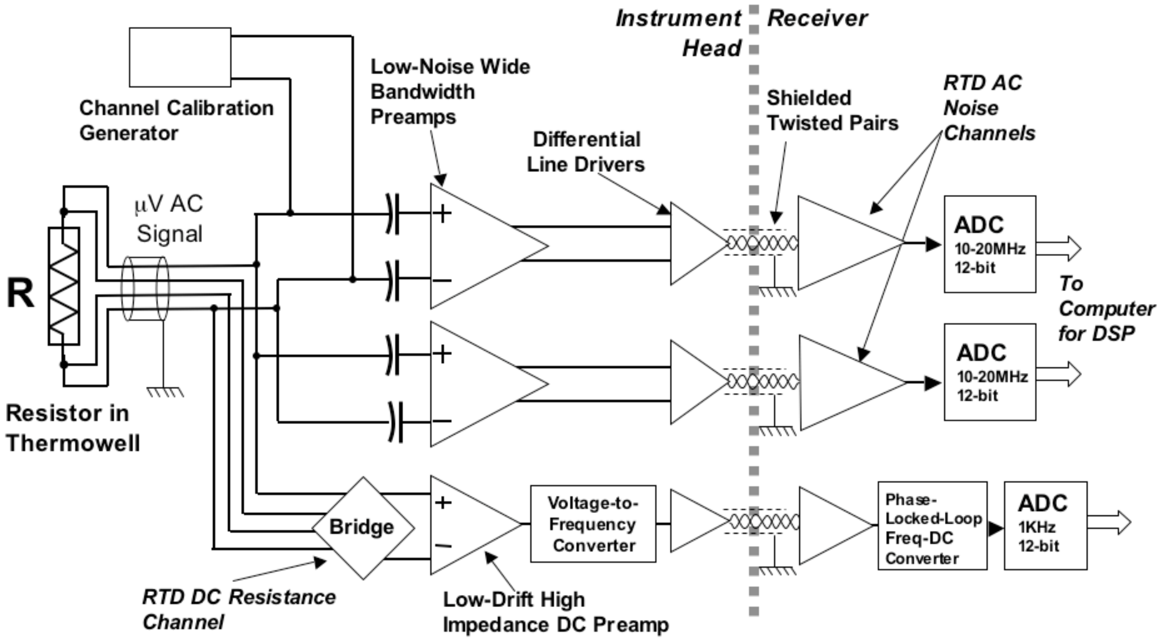

Figure 5. Principal Components And Conceptual Configuration Of The Dual Mode Resistance And Johnson Noise Thermometer Incorporating the Cross-Correlation Technique, Digital Signal Processing, and Channel Gain Calibration.

In a power reactor implementation the preamplifier head box would be located at the proximal end of the resistance probe (or at most ~10 m from the sensor) in a more challenging radiation and temperature environment. The digital signal processing would be located near the control room in as benign an environment as possible.

4. CONCLUSION

Johnson noise thermometry is becoming progressively more possible for long-term, high-reliability implementation as signal processing technology progresses and engineering expertise is applied. The principal advantage of JNT is the fact that it is an ab initio type measurement and the consequently does not require recalibration. However, JNT remains a complex measurement requiring skill and care in its implementation. Notably the drift of the entire measurement system must be removed from the reported temperature as opposed to merely the drift in the electrical resistance of the sensor.

5. REFERENCES

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