CAL LAB

THE INTERNATIONAL JOURNAL OF METROLOGY

2006
OCTOBER
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DECEMBER

Innovative ADC Sets New Temperature Calibration Standards

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Better Accuracy in Temperature Calibration and Measurement through a New Type of Analog-to-Digital Converter

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This article describes a new reversal-switched DC precision thermometer that achieves performance levels previously attained only with AC resistance bridges. The microK is designed for use in secondary temperature calibration and high accuracy temperature measurement applications (to 0.4mK uncertainty) and is the only precision thermometer that can work with both resistance thermometers and thermocouples at sub mK uncertainties. The use of a touch-screen interface and the elimination of switches, relays and potentiometers from the design make this the first solid-state instrument of its type, thereby providing the highest possible reliability. The core technology is a wholly new type of ADC (analog-to-digital converter) based on the □-Δ (sigma-delta) technique but in which the single-bit DAC (digital-to-analog converter) in the feedback loop is replaced by a 5-bit PWM (pulse-width modulation) DAC. The effect of this is to reduce the quantization noise from the □-Δ ADC technique by more than two orders of magnitude. The noise performance is then determined by the electronic devices used in the ADC and measurement system, which are lower than existing comparable instruments.

Introduction

Although we rightly focus on the thermodynamic challenges when making high accuracy temperature measurements, the electrical measurement requirements for achieving low measurement uncertainty are comparable to those of a good electrical laboratory. The main temperature sensors used are PRTs (platinum resistance thermometers). The SPRTs (standards PRTs) used in high accuracy calibration work comprise thin and lightly suspended coils of platinum wire, the resistance of which is measured to determine their temperature.

With a nominal temperature coefficient of $0.1\Omega K^{-1}$ for a 25Ω SPRT, we need to measure resistance to 100$\mu\Omega$ in order to achieve a 1mK temperature uncertainty. Typically, a 1mA sense current is used with a 25Ω SPRT in order to minimise self-heating, so the voltage uncertainty corresponding to 1mK is only 100nV over a range of typically 0-100mV (to accommodate the full temperature range of the SPRT). This requirement represents a demanding electrical measurement objective.

Thermocouples are commonly used in measurement applications. Noble metal thermocouples are used for high accuracy calibration work at higher temperatures (above ~1000°C) where PRTs can no longer operate. The EMF generated by a thermocouple is measured in order to determine its temperature. Again, the demands on the electrical measurement rival those of the electrical calibration laboratory; a gold-platinum thermocouple has an EMF coefficient of nominally $20\mu VK^{-1}$ at 1000°C, so in order to measure to 10mK requires measuring its EMF to 200nV over a range of 0-20mV (to accommodate the full range of the thermocouple). This again represents a demanding electrical measurement objective.

The Need for a New ADC

The ADC in a precision instrument is the "measurement engine." Its performance is the starting point for achieving low measurement uncertainty. Historically, AC bridges (or other transformer based measuring systems such as current comparators) have been used in temperature laboratories requiring performance better than 1mK uncertainty. These use a ratio-transformer as their ADC. In an AC resistance bridge, a common AC current is passed through the SPRT (R_X) and Reference Resistor (R_S). The voltage generated across R_S is scaled using the transformer and compared with the voltage across R_X. A control circuit adjusts the

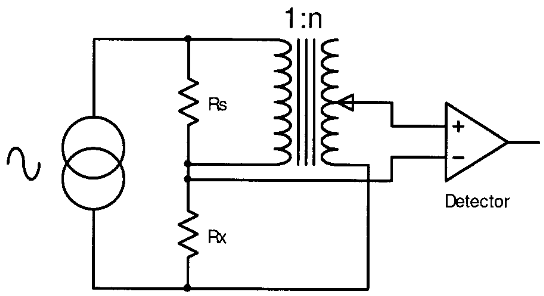

Figure 1. AC bridge.

transformer tapings to balance the bridge and drive the "error" signal to zero. Since the ratio of the voltages across the primary and secondary of an ideal transformer is equal to the turns ratio, then $R_X = nR_S$. Using this technique, the ASL F700 can achieve an accuracy of 0.5ppm.

For less demanding work (uncertainties above 1mK) DC potentiometric instruments can be used, typically employing integrating ADCs. A common DC current is passed through a thermometer (R_X) and reference resistor (R_S). A voltmeter is switched between reading the voltage across R_X and R_S and the ratio of the two readings (n) is calculated. The value of R_X is then determined from $R_X = nR_S$. The effect of thermal EMFs can largely be eliminated by reversing the current and averaging measurements with opposite current polarity.

The Hart Superthermometer uses the Thaler ADC100 as its ADC. Although the core ADC100 only claims a linearity of 3ppm, additional linearization of the instrument allows the Superthermometer to achieve an accuracy of 1ppm.

Most temperature calibration laboratories require a resistance bridge or precision thermometer for use with PRTs and a separate precision voltmeter or DMM (digital multi-meter) for use with thermocouples. The new precision thermometer (microK) described here uses a DC measurement technique so that it can measure both resistance and voltage but achieves higher performance than is normally available from DC measurement techniques. Consequently, this is the only instrument that can work with both resistance thermometers (PRTs and thermistors) and thermocouples at sub mK precision.

The advantage to users is that they only need to purchase one instrument rather than two, saving both capital expenditure and running costs (only one instrument requiring regular, traceable calibration).

A key design objective for the new microK was that it should contribute significantly less than 1mK to the uncertainty budget in a typical measurement application (25Ω SPRT at 1mA). However, since the best available ADCs do not offer the noise and linearity performance required for sub-mK performance, we needed to develop a completely new ADC for this application.

A New ADC

The ADC system developed for the microK is based on the well established Σ-Δ technique [1]. The new design uses a multi-bit Σ-Δ technique originally developed by Metron Designs and the National Physical Laboratory in the UK. It has been further enhanced to meet the demanding requirements of the new microK instrument.

Although Σ-Δ ADCs with very high resolution are available as single integrated circuits, the noise performance and linearity of these devices does not match their excellent resolution. In a conventional Σ-Δ ADC, the analog input signal is subtracted from the output of a 1-bit DAC before being filtered by a series of cascaded integrators. The signal then passes to a 1-bit ADC that drives the DAC and forms a feedback loop.

The extremely high, low-frequency loop-gain of the cascaded integrators ensures that the input signal is balanced against the output of the DAC so that the average value of the 1-bit data stream from the DAC equals the input signal. A low-pass digital filter is then used to extract the converted value from the 1-bit data stream.

Another way of viewing the operation of a Σ-Δ ADC is to consider what is happening in the frequency domain. The over-sampling used in Σ-Δ converters means that the quantization noise caused by the 1-bit ADC is spread over a wide bandwidth, whereas the signal we are looking for is unaffected by this over-sampling. The digital filter selects the narrow bandwidth of the required signal. The amount of quantization noise in this bandwidth is relatively small because the over-sampling spreads the noise power over such a large bandwidth.

The noise on the converted signal can be reduced by increasing the sampling rate, but it becomes increasingly difficult to maintain performance as the clock rate of the system becomes higher. Another way to reduce the noise would be to use a multi-bit ADC and DAC in the feedback

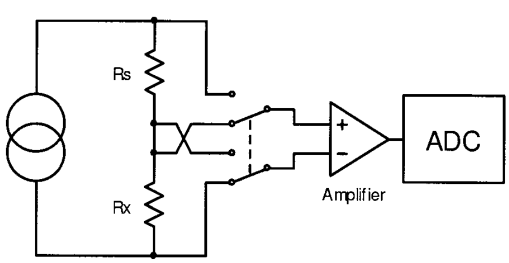

Figure 2. DC resistance instrument.

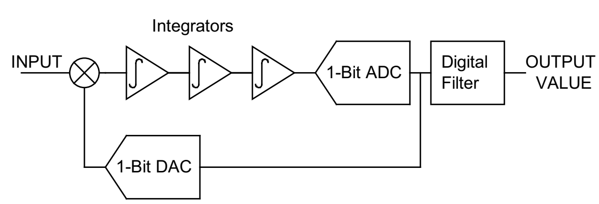

Figure 3. Conventional Σ-Δ ADC.

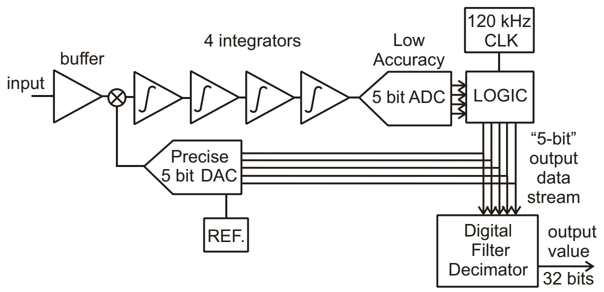

Figure 4. □-Δ ADC with 5-bit feedback.

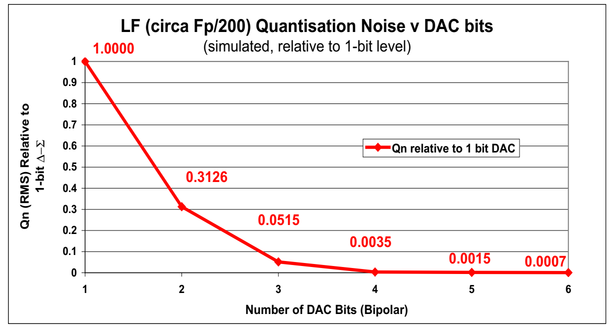

Figure 5. Effect of ADC/DAC resolution on noise.

loop. This would not normally be a sensible approach since the DAC would carry the full accuracy burden of the measurement system. However, by using a PWM DAC, in which the output is a signal of fixed frequency and amplitude but variable pulse width, we turn the problem of producing accurate voltage or current levels into one of accurate timing. Whereas achieving sub-ppm voltage accuracy with a DAC would not be feasible in this sort of product, it is possible to achieve the corresponding timing accuracies.

The timing demands of the PWM DAC are, however, far from trivial. The digital filter has to work at the Σ-Δ ADC's clock rate. In the microK, this digital part of the Σ-Δ ADC is implemented in a fast FPGA, which provides both the digital filter that decimates the DAC output (to extract the converted value) and controls the feedback DAC. The full-scale pulse-width on the PWM DAC is only 5μs, so the 0.2ppm linearity achieved with the ADC corresponds to a timing accuracy of 1ps, or about the time it takes for the electrical signals in the control system to travel 0.3mm. The development of the core technology to achieve this performance represented almost half the total time and cost of the project.

It might appear that the reduction in quantization noise from using multi-bit feedback in a Σ-Δ ADC would be directly proportional to the ADC/DAC resolution. However, the reduced differential gain inherent in the higher resolution DAC greatly improves loop stability too. This allows the use of more orders of integration and higher loop gain giving a disproportionate improvement in quantization noise [2].

This disproportionate improvement occurs up to about 4 or 5 bits, but thereafter the noise becomes proportional to the ADC/DAC resolution. In the microK, we chose to use 5-bit resolution, this gives a predicted reduction in quantization noise of a factor of over 600. In practice this means that the quantization noise is no longer dominated by the Σ-Δ technique and is instead limited by the performance of the electronic devices used in the ADC and the rest of the measurement system.

Another benefit of the new ADC is its speed. The implementation used in the microK provides conversions to full accuracy in 100ms. This, together with the use of solid-state switching, allows for a very fast reversal rate, which in turn helps to eliminate the effect of any thermal EMFs and reduce the noise (since the system can operate above the corner frequency of the amplifier's 1/f noise).

Thermal EMFs

Thermal EMFs (EMFs generated as the result of junctions between dissimilar metals at different temperatures) are a potential source of error when working at this precision. These can largely be eliminated when measuring resistance thermometers by reversing the current and averaging the measurements (the offsets in the two measurements cancel each other out when the readings are averaged together). However, this technique cannot be used when measuring temperature with thermocouples, so the thermal EMFs need to be eliminated at source. For this reason, we used tellurium-copper (gold plated) as the connector contact material, since this combines good mechanical properties with extremely low thermal EMFs against the copper terminations of a thermocouple.

In order to eliminate thermal EMFs from the measurement system (already small), the input connections are reversed immediately behind the input terminals. Measurements made with and without the reversal are then averaged together to eliminate the thermal EMFs. The limitation is then the thermal EMFs generated by the devices used to implement this reversal.

Solid-State Switching

One of the most common sources of failure in instruments of this type is the contacts in switches, relays, connectors and potentiometers. For this reason, the microK was designed to have no switches (apart from the line/mains switch), mechanical relays or potentiometers. The switches typically used for the operator interface have been replaced with a combination of an industrial grade touch-screen over a full-color VGA LCD, making the instrument both reliable and easy to use. The internal connectors are limited to three ribbon cables (with gold plated contacts) for signal interconnections plus a small number of connectors for the AC power and internal DC supply.

Instruments addressing this market have so far used mechanical relays for some or all of the signal routing. In moving to semiconductor switching there was some concern about the associated thermal EMFs. We were conscious that the metal-silicon junctions in the devices would generate higher thermal EMFs than mechanical relays under the same temperature gradient. But, the very small size of the die within the semiconductor devices means that there would be little opportunity for thermal gradients, giving them a strong advantage over their mechanical counterparts. In practice we found that the thermal EMFs from solid-state switching are significantly less than even the best mechanical relays. As a result, we can achieve voltage offsets significantly less that 100nV at the input to the microK instrument. This is better than most of the high performance voltmeters currently used to measure thermocouples in temperature calibration laboratories.

Substitution Topology

A significant source of error in the potentiometric measurement topology shown in Figure 2 is the common-mode rejection ratio of the input amplifier. The common-mode signal at the input to the amplifier changes between the two measurements and will lead to an error at the input to the ADC. In order to eliminate this source of error, the microK uses a substitution topology in which there is a single point of measurement in the system into which the SPRT and reference resistor are switched alternately.

This adds complexity and cost to the design, but ensures that there is no change to the common-mode signal between the measurement of the reference resistor and the thermometer. This approach would normally, however, increase the demands on the current source. In the conventional topology, the current is common to both the reference resistor and the thermometer. In the

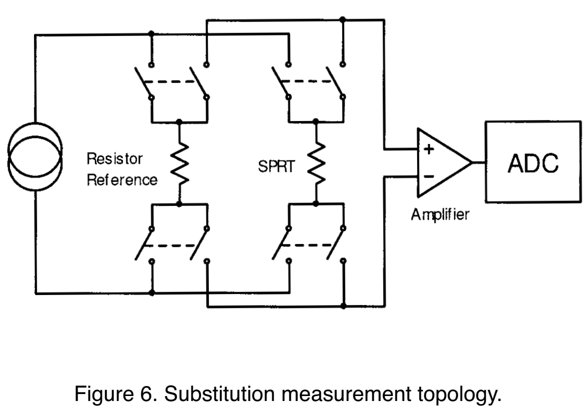

Figure 6. Substitution measurement topology.

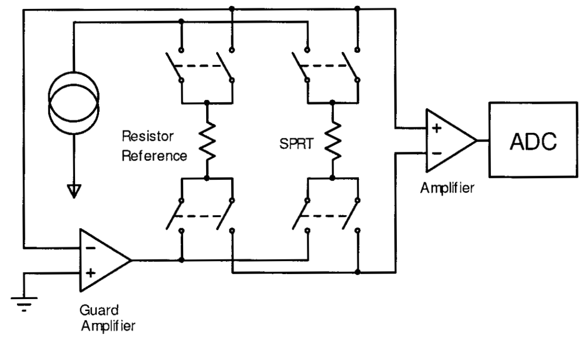

Figure 7. Guarded measurement system.

substitution topology, the voltage at the output of the current source changes between the measurement of the SPRT and the reference resistor, and the current source must accommodate this change without any significant change to the sense current.

The current source in the microK has a very high output impedance, such that the sense current will not change significantly between the measurement on the reference resistor and the thermometer. In addition, the whole measurement system is actively guarded so that both the voltage at the output of the current source and the common-mode voltage across the device being measured do not change.

The guard amplifier senses the potential at the "top" of the measurement system and drives the opposite end in order to maintain it at ground potential. In this way, both the current source and amplifier see no change in voltage/common-mode signal between the measurements of the reference resistor and the SPRT.

Inherent Stability

The current reversals used to eliminate thermal EMFs from resistance measurements together with true 4-wire resistance measurement have the effect of ensuring an intrinsically stable zero with time and temperature. The voltage at the amplifier input when measuring a short-circuit will be the same whichever current direction is used. The process of averaging (the magnitude of) the measurements therefore yields zero (with uncertainty determined by the system noise).

In a similar way, the substitution technique means that the measurement system is also inherently stable at unity ratio since the voltages measured for a reference resistor and thermometer of the same value will be identical. There is, after all, no difference between these two measurements apart from the fact that they are taken at slight different times. The system noise will again determine the uncertainty of this unity ratio measurement.

Eliminating Self-Heating Effects

Although the sense currents used with SPRTs are small, they can still generate self-heating "errors" of several mK. The most accurate SPRTs typically have very lightly supported elements so the self-heating effect is ironically worst in those SPRTs designed for the most accurate measurements.

The microK includes individual "keep-warm" current sources for each of the three input channels, These replace the sense current when a channel is not being measured and ensure that the power dissipated in an SPRT remains constant.

The most accurate measurements with an SPRT involve measuring its resistance at two sense currents and then extrapolating back to the zero-power value [3]. The microK's user interface provides a simple feature to allow the sense current to be scaled by a factor of root-two (a factor of 2 in power) to make this technique easy for the user to implement.

Three Channels for Best Practice

The rather unusual choice of three measurement channels arose from the trend amongst accreditation bodies to recommend the use of two reference thermometers when performing a comparison calibration. The microK is equipped with three input channels so that the resistance of the thermometer being calibrated (DUT) and two reference PRTs can be measured against the internal reference resistors without the need for an external multiplexer. It is interesting to note that any small errors in the value of the internal reference resistors has negligible effect on a comparison calibration since the error in the measured resistance of the DUT corresponds to the error in the temperature indicated by the SPRTs provided the temperature coefficient (of resistance) for the DUT and SPRT are the same. Any net errors will be the product of the small error in the internal reference resistor and the difference between the temperature/resistance slopes for the reference and DUT thermometers. This can be calculated and will invariably be insignificant.

Factors Limiting Performance

The largest contributor to the uncertainty of resistance measurements on SPRTs is the reference resistor. For this reason, the highest quality Vishay bulk metal foil resistors have been used. These are all housed in hermetically sealed packages, apart from the 1Ω standard (which is not available in a hermetic package and is therefore conformally coated). The stability of these internal resistance standards is better than 5ppm/year. For the best stability, external resistors such as Wilkins standard resistors maintained in an oil bath should be used. Experience shows that the stability of such a system is typically <1ppm/year.

The stability of the microK for voltage measurements is determined principally by the internal voltage reference. The device used is a zener reference similar to those used as voltage transfer standards in electrical metrology applications. The overall stability of the voltage system (including the zener diode and all other circuits) is 3ppm/year.

Performance with RTDs

The testing and performance validation of the measurement system presented challenges comparable to the product designs itself. Since the most accurate thermometry work is done with SPRTs, the performance of the resistance measurement system is considered to be the more critical. This has been thoroughly tested using an RBC (resistance bridge calibrator) from 2K Electronics of New Zealand. The RBC contains four high stability resistors that can be connected in series/parallel combinations to give up to 70 different resistance ratios. The specification of the RBC (better than 0.01ppm) is more than adequate to test the new measurement system [4].

The accuracy of the RBC purchased for the project was verified by checking it against two ASL F900 AC resistance bridges (having 0.02ppm accuracy), one at the National Physical Laboratory and the other in Isothermal Technology's primary temperature laboratory. Both tests showed agreement within 0.01ppm, giving confidence in the performance of the RBC.

Tests on the microK-400 (specified accuracy 0.4ppm) show that the typical accuracy is 0.25ppm, as shown below for unit 06-B002 which simulates a 25Ω SPRT at 1mA over its full operating range.

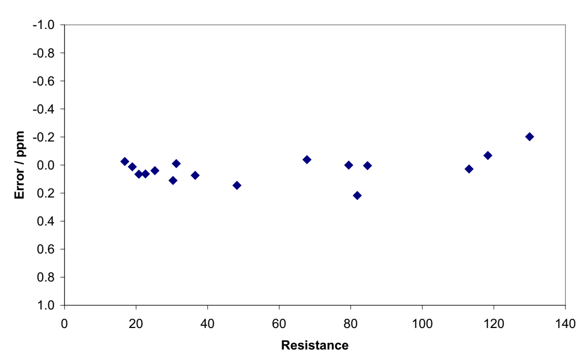

Figure 8. Accuracy of microK-400.

Performance with Thermocouples

The temperature uncertainty targets associated with thermocouples (even noble metal thermocouples) are much less demanding than those of SPRTs. However, the low EMFs produced by thermocouples mean that these temperature uncertainties still translate into demanding electrical measurement uncertainties. A gold-platinum thermocouple has an output range of 0-20mV. With an EMF coefficient of $20\mu VK^{-1}$ at 1000°C, the means that a 10mK temperature uncertainty translates to a 200nV voltage uncertainty.

The measurement system used to measure voltage is a subset of that used for resistance measurements. The tests performed to verify the linearity of the resistance measurement system are therefore considered to verify the linearity of the measurement system for voltage measurements. However, voltage measurements still require measurements at zero and full scale in order to test and calibrate them. At present this is achieved using a stable voltage source together with a precision DVM (digital voltmeter). However, the uncertainties achievable with this technique currently limit the accuracy that we can specify for the microK product.

In general, it is difficult to find commercial products or systems to perform voltage calibrations at the 20-100mV range with uncertainties of 100nV, where we wish to work. Metron Designs are therefore working on a new system for low voltage, high accuracy calibration. This will comprise a precision current source that can be calibrated (traceably) to 1ppm in combination with Wilkins resistors that are maintained in a temperature controlled oil bath. This is particularly useful, since calibrated resistance standards of the required values (1Ω and 10Ω) are commonplace in temperature laboratories. The stability of the current source and Wilkins resistors means that we expect to achieve voltage uncertainties of better than 100nV at the 20mV level. This will be the basis of a future publication.

Conclusions

The new Σ-Δ ADC with multi-bit, PWM feedback provides better linearity and noise performance than previous Σ-Δ or integrating ADCs. This new technology enables the microK product to offer performance levels in a DC potentiometric instrument that were previously only achievable with AC resistance bridges. The use of DC measurement technology means that, unlike AC bridges, the microK works with thermocouples as well as PRTs. The microK therefore replaces the two instruments normally required for a temperature laboratory (a resistance bridge and a precision DVM), saving users capital cost and running costs (only one instrument on which to maintain traceable calibration).

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