XX IMEKO World Congress
Metrology for Green Growth
September 9−14, 2012, Busan, Republic of Korea

UNCERTAINTY ASSESSMENT OF RESISTANCE THERMOMETRY BRIDGES

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Abstract: Despite the importance of resistance bridges in thermometry, an accurate assessment of their uncertainty has not been investigated much. Among various uncertainty components, nonlinearity and ratio error have been of particular interest, and a Hamon-type resistance network known to be RBC (resistance bridge calibrator) is widely used to measure those uncertainties. However, due to finite temperature coefficients of base resistors in the RBC, the evaluated uncertainty of the resistance bridges under normal operating environment is in doubt. In this work, to accurately evaluate the uncertainty of the resistance thermometry bridge, an air medium thermostatted chamber was devised, and the nonlinearity and ratio error of a resistance bridge at KRISS (ASL F900) were assessed. Along with this, repeatability and AC quadrature/frequency dependence of the resistance bridge were evaluated and total combined uncertainty of the resistance bridge at KRISS was finally assessed.

Keywords: Resistance Thermometry Bridge, Nonlinearity, Ratio Error, Repeatability, Frequency Dependence, Resistance Bridge Calibrator.

1. INTRODUCTION

Resistance measurement is a fundamental practice in resistance thermometry, and thus, resistance thermometry bridges, which measure resistance ratios of standard platinum resistance thermometers (SPRTs) to standard resistors, are of prime importance in thermometry. As with other instruments in measurement chain, the resistance bridges contribute to the overall uncertainty of the measurements, and various factors have been known to comprise the uncertainty of the resistance bridges. Especially, nonlinearity, ratio error, repeatability, and AC quadrature/frequency dependence, which have been considered as the main factors determining the accuracy of the bridges, need accurate quantitative assessments for reliable measurements [1-3].

For evaluation of those four uncertainty factors, thermally stabilized standard resistors of known resistances can be used to measure nonlinearity, ratio error, and repeatability. However, as the simple standard resistor applied method only gives confidence building level information about the existence of the nonlinearity and the ratio error, these two factors necessitate special devices and schemes to evaluate them correctly.

Among various methods for the nonlinearity and ratio error assessment, a Hamon-type resistance network known as RBC (resistance bridge calibrator) is widely used, and has been known to measure these uncertainties to a few factors below the manufacturers' specification [1, 4]. However, as the accuracy of the present resistance bridges increase, the uncertainty caused by the RBC itself doubts the reliability of the measured accuracy of the bridges. Especially, as the base resistors have finite temperature coefficients (i.e., 0.3 ppm/℃), the evaluated nonlinearity and ratio error of the resistance bridges under normal operating environment could lead to unacceptably large uncertainties [5-7]. Therefore, in order to improve the reliability of the measured nonlinearity and ratio error, precise temperature control around the RBC is critical.

In this work, the four aforementioned uncertainty factors of the resistance thermometry bridges at KRISS are quantitatively assessed. Particularly, to accurately evaluate the accuracy of the resistance thermometry bridges, an air medium active thermostatted chamber having peak-to-peak temperature stability of around 0.1 ℃ was devised, and using this chamber the nonlinearity and the ratio error were assessed.

2. UNCERTAINTY ASSESSMENT

2. 1. Nonlinearity and Ratio Error Assessment by Resistance Bridge Calibrator

The nonlinearity and ratio error of the resistance bridges are consequences of physical imperfections of the bridges, and manifest themselves as deviations from the linearity of the measured resistance ratios and the complement check (i.e., unity), respectively. Thus, ideally, using simple series connections of known resistors and complement check of those resistors can detect those uncertainty factors of the resistance bridge, but limited numbers of realized resistance ratios and the need for the calibration of the resistors render the effectiveness of this test merely a confidence-building level.

The RBC comprises four base resistors of carefully chosen different resistances, and by series and parallel combinations of these resistors, can produce up to 70 distinct resistance ratios using normal and reciprocal connections to the resistance bridge. Moreover, as the linearity of the realized resistance ratios is calculated not by the predetermined resistances of the base resistors but by the least square fitted values of these base resistances, the need for the calibration of the base resistors is automatically resolved. Due to these benefits, the RBC is widely used for assessment of the accuracy of the resistance bridges, and the accuracy of the resistance bridge is calculated by the standard deviation of the measured resistance ratios from the calculated linearity. The standard uncertainty is calculated using the following equation.

$$u^2 = \frac{1}{N-4}\sum_{i=1}^{N}\left(R_{i,meas} - R_{i,calc}\right)^2 \qquad (1)$$

where N is the number of input resistance ratios, $R_{i,meas}$ is the measured resistance ratios, and $R_{i,calc}$ is the calculated resistance ratios from the least square fitted base resistances.

Despite these advantages of the RBC, the RBC has an intrinsic limitation on its accuracy. As mentioned earlier, the nonzero temperature coefficients of the base resistors could introduce unacceptably large uncertainties on the measured nonlinearity. Furthermore, due to the manually operated nature of the RBC, continuous operation of the RBC in a precisely temperature controlled environment is hardly achievable or requires expensive air-conditioning system for the entire measurement room. Therefore, an effective small scale thermostatted chamber with ability to manipulate the RBC without thermal contact to the outer environment is highly required.

In this work, an active small scale thermostatted chamber using thermoelectric modules as coolers and resistive heaters as heating elements was developed for accurate measurement of the nonlinearity and the ratio error of the resistance bridges. Especially, in order to improve stability of the temperature around the RBC, a separate inner chamber containing only the RBC was employed. This dual chamber structured thermostatted chamber is also designed to allow the manipulation of the RBC without thermal contact to the outer environment using specially devised mechanisms. Thus, continuous measurement of the whole range of resistance ratios without interruption was possible. Figs. 1 and 2 show the front and top section views and dimensions of the thermostatted chamber.

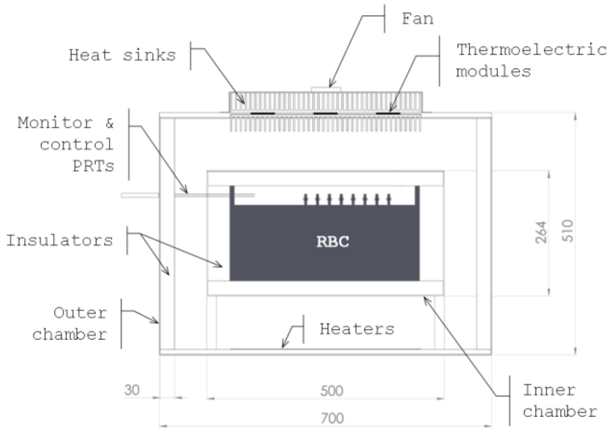

Fig. 1 Front section view of the thermostatted chamber.

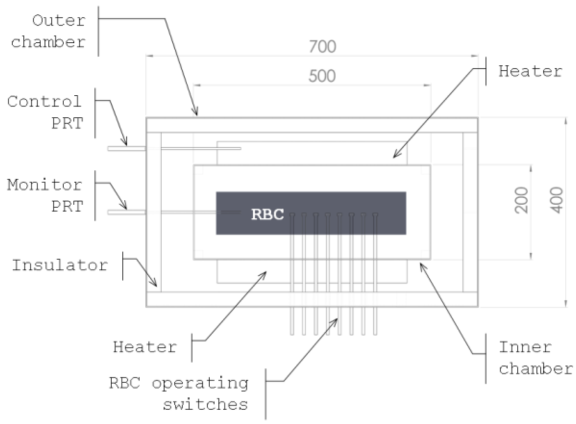

Fig. 2 Top section view of the thermostatted chamber.

As shown in the figures, the thermoelectric modules and heaters were placed top and bottom inner surfaces of the outer chamber to facilitate heat exchange inside the chamber. Six 75 W rated thermoelectric modules having a maximum temperature difference of 68 ℃ were used, and to enhance heat transfer between the modules and surrounding medium, heat sinks and a fan were equipped on each side of the module (the fan was only used on the heat dissipation side of the thermoelectric modules). The thermoelectric modules were operated at a fixed voltage which was adjusted not to condense moisture in the outer chamber.

The air temperature of the outer chamber was controlled by the two resistive heaters and a commercial PID temperature controller. The control variable was the inside air temperature of the outer chamber, which was measured by the control PRT as shown in Fig. 2, and varying the input power to the heaters the air temperature was controlled within the temperature controller's resolution (i.e., ± 0.1 ℃). In addition to this, to further decrease the temperature variation which was mainly short term instability caused by the heat exchange between the coolers and the heaters, a separate chamber only for the RBC was placed inside the outer chamber. With this configuration, it was possible to achieve a peak-to-peak temperature variation of around 0.1 ℃.

2. 2. Repeatability and AC Quadrature/Frequency Dependence Assessment

The uncertainties due to the repeatability of the resistance bridge was evaluated as the standard deviation of the measurements for around 12 hours with thermally stabilized standard resistors having nominal resistances of 25 Ω and 100 Ω, respectively. The AC quadrature/frequency dependence of the resistance bridge was calculated by the difference between the low (30 Hz) and high frequency (90 Hz) measurements at a corresponding fixed point. In this work, only triple point of water was used to evaluate the AC quadrature/frequency dependence.

3. TEST RESULTS

3. 1. Optimum Operating Condition

The accuracy of the resistance bridges are known to be dependent on the operating conditions of the bridges. Especially, gain and bandwidth of the bridges were reported to be influential to the measured nonlinearity [3, 8]. Thus, prior to measuring the nonlinearity and the ratio error, it was necessary to find an optimum operating condition at which the measured nonlinearity was guaranteed far below the manufacturer's specification. To this end, nonlinearity of a resistance thermometry bridge (ASL F900, S/N: 7432 003 003) was assessed at various gain and bandwidth combinations, and Table 1 and Fig. 3 show the measured nonlinearity at those operating conditions.

TABLE 1. Nonlinearity variation with gain and bandwidth change.

Gain	**Bandwidth, Hz**	**Nonlinearity × 10^9**	**$\Delta T_{RBC,\ peak\text{-}to\text{-}peak}$, ℃**
10^3	0.1	589.52	0.10
10^4	0.1	77.40	0.09
10^5	0.1	11.34	0.09
10^4	0.05	74.42	0.12
10^4	0.1	77.40	0.09
10^4	0.2	76.89	0.10

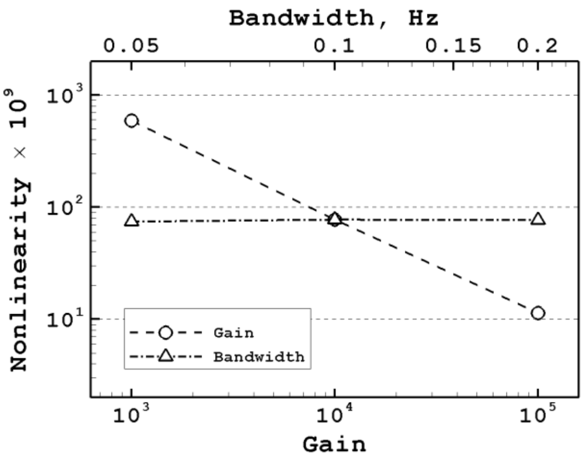

Fig. 3 Effect of gain and bandwidth on the measured nonlinearity (reference combination: 10^4, 0.1 Hz).

As shown in the figure, there was a clear gain dependence of the nonlinearity but negligible effect of the bandwidth. Especially, due to the fact that the nonlinearity below the manufacturer's specification was only possible with gain of 10^5, and the bandwidth had negligible effect on the measured nonlinearity, the gain of 10^5 and bandwidth of 0.2 Hz were chosen as the optimum operating condition for the tested resistance thermometry bridge.

3. 2. Nonlinearity and Ratio Error

With the obtained optimum operating condition (i.e., 10^5 gain and 0.2 Hz bandwidth) and the thermostatted RBC, the nonlinearity and the ratio error of a resistance thermometry bridge at KRISS (ASL F900, S/N: 7432 003 003) were assessed. In addition to this, a simple ratio complement check using standard resistors of the same nominal resistances (i.e., 100 Ω) was carried out to ensure the measured ratio error reliable. The ratio error by the simple complement check was determined from the following equation.

$$u_{RE} = \frac{\left[1-\left(R_1/R_2\right)\left(R_2/R_1\right)\right]}{2} \qquad (2)$$

where R_1 and R_2 are the resistances of the standard resistors of nominally the same resistances (here 100 Ω).

Also, in this work, a different resistance thermometry bridge of the same type (ASL F900, S/N: 8710 005 014) were tested and compared to examine the consistency in the measured nonlinearity and ratio error. Table 2 shows the measured nonlinearity and ratio error of those resistance bridges and results of simple ratio complement check.

TABLE 2. Measured nonlinearity and ratio error at optimum operating condition.

Bridge S/N	**Nonlinearity × 10^9**	**Ratio error × 10^9**	**Combined uncertainty × 10^9**
7432 003 003	11.54	17.72	20.65
Complement Check		9.45	-
8710 005 014	11.85	9.11	14.95

As shown in Table 2, the two resistance bridges showed similar nonlinearities implying that the measured nonlinearity was consistent regardless of specific bridges tested. However, the measured ratio error showed significant difference between those bridges and from the result of the simple complement check. Despite this difference in the ratio error, as the combined uncertainty did not exceed much the stated accuracy of the bridge (i.e., 20 ppb), it was assumed that the measured ratio error was reliable.

3. 3. Repeatability and AC Quadrature/Frequency Dependence

The repeatability of the resistance thermometry bridge was assessed by measuring standard deviation of the readings for around 12 hours. Fig. 4 shows the measured deviations of the readings from the average, yet only 1 of 20 balanced readings is depicted for better legibility. As shown in the figure, the readings were within 10 ppb of the average of the readings, and the calculated repeatability was 3.64 ppb.

As for the measurement of the AC quadrature/frequency dependence, triple point of water resistance was measured at two difference operating frequencies (i.e., 30 Hz and 90 Hz). The SPRT used for these measurements was Leeds & Northrup 8153Q (S/N: 1354028), and the triple point of water cell was the national standard of Korea (homemade, S/N: TPW 2000-24). Table 3 shows the measured results and the AC quadrature/frequency dependence in temperature scale.

TABLE 3. Measured AC quadrature/frequency dependence.

Frequency	0 mA current resistance, Ω	Difference, μK
30	25.540 786 3	236
90	25.540 762 3	

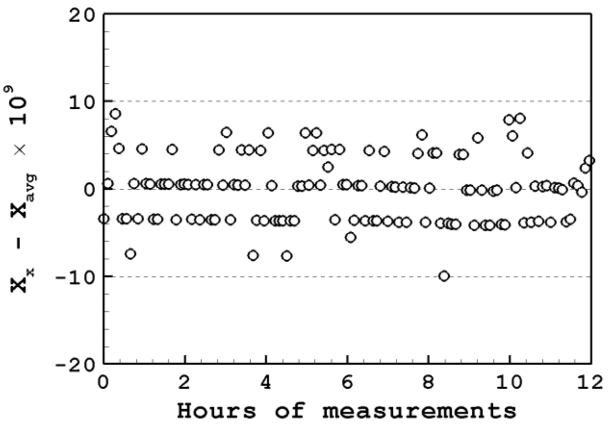

Fig. 4 Repeatability of the resistance thermometry bridge

3. 4. Combined Uncertainty

From the results above, the combined uncertainty of the resistance thermometry bridge at KRISS was assessed. Table 4 shows the assessed uncertainty components and the combined uncertainty in temperature scale. Here, as the ratio error of the resistance bridges did not propagate into the resistance ratios of interest and affect the measured temperature, the ratio error did not counted for the combined uncertainty.

TABLE 4. Uncertainty components of the resistance bridge at KRISS and combined uncertainty at triple point of water.

Uncertainty component	Uncertainty $\times 10^9$	Uncertainty, μK
Nonlinearity	11.54	25
Ratio error	17.72	39
Repeatability	3.64	8
AC quadrature/frequency dependence	-	236
Combined uncertainty	-	238

As shown in the table, the most dominant uncertainty component of the resistance bridge was the AC quadrature/frequency dependence, which overwhelmed the effect of other uncertainty components. However, rather than the intrinsic uncertainty of the resistance bridge, the AC quadrature/frequency dependence was due to the structural vulnerability to the frequency change of the thermometer used. Thus, it was concluded that the AC quadrature/frequency dependence of the resistance measurement at fixed points should be carried out with proper thermometers and applied in the corresponding uncertainty assessment.

4. CONCLUSION

In this work, various uncertainty components of a resistance thermometry bridge at KRISS were assessed. The assessed uncertainty components included the nonlinearity, ratio error, repeatability, and the AC quadrature/frequency dependence. As for the uncertainties related purely to the resistance thermometry bridge (i.e., the nonlinearity and the ratio error), the measured uncertainty was equivalent to the stated accuracy of the manufacturer's specification, thus justifying the use of high precision thermometry resistance bridges. However, the measured AC quadrature/frequency dependence, which was intrinsic limitation of using AC type resistance bridges, far outweighed the other uncertainty components supposedly due to the structure of the thermometer used. Therefore, it was concluded that proper assessment and application of the AC quadrature/frequency dependence was necessary for accurate temperature measurement and corresponding uncertainty evaluation.

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