

## NONLINEARITY TESTING OF EQUIPMENT USED IN TEMPERATURE MEASUREMENTS

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**Abstract** – In this paper the nonlinearity testing of seven resistance instruments used to measure temperature is presented. Tested were four multi-meter type instruments which use the UI method to determine resistance and three resistance bridges that measure resistance as a ratio between a resistance thermometer and a standard resistor.

The device used to measure the nonlinearity of the instruments was a RBC100 resistance bridge calibrator. The device is a passive four resistor matrix that enables for 35 different resistances to be generated by parallel/series switching of the four base resistors. The device had been previously automated for easier use [6]. This eliminates the need for an operator to be present during calibration, the device can also be placed in an thermally stable enclosure and switched from within it. The software that was purposely developed for the automated work with the RBC100 controls both the calibrator as well as gathers measurements from the instrument under test. The software also calculates non-linearity and keeps record of the measurements that were performed.

During testing, two rounds of measurement sets were performed. During each round 3 sets of all 35 combinations were measured on every instrument under test. The multi-meter type instruments nonlinearity was measured to be far lower than the declared uncertainty. The linearities of the resistance bridges were in most cases equal to the declared uncertainty value. This was however to be expected, since bridge nonlinearity accounts for the major part of its uncertainty. Non-linearities were in the range from 380  $\mu\Omega$  (6  $\frac{1}{2}$  digit multi-meter) down to 2  $\mu\Omega$  (best resistance bridge).

**Keywords:** resistance bridge, SPRT, non-linearity

### 1. INTRODUCTION

Temperature realization and measurement on the primary and secondary level is mostly being done by national metrology institutes (NMIs). These laboratories use standard platinum resistance thermometers to convert temperature into an electrical quantity, resistance. This means that the quality of temperature measurement is dictated by the quality of resistance measurement.

Primary and secondary laboratories use two types of instruments to measure resistance with low uncertainty. The first type of instruments are represented by classic electric instruments (“multimeters”), which measure resistance using the UI method (a known current is passed through the measured resistor and the voltage drop is then measured to calculate the resistance value). The uncertainty of the measured resistance for this type of instruments is dependant on the accuracy and stability of the measuring current as well as the uncertainty of the AD converter used to measure the voltage drop on the measured resistor. These constraints make this type of instruments able to measure resistances down to uncertainties of 1ppm at best. The best instruments of this type are the HP34401A multimeter, the HP3458A multimeter, the HP34420A nanovoltmeter and similar instruments from other manufacturers.

In primary and secondary laboratories where the uncertainty, to which resistance needs to be measured, is bellow 1 ppm, other types of instruments are used. These instruments are AC and DC resistance bridges. Both use a similar principle of measurement, where a precision ratio transformer is used to determine the resistance ratio of two resistors. The measured resistor  $R_x$  (in temperature measurements the SPRT) is compared to a standard resistor  $R_s$ , the result of measurement is a ratio  $n$  of both values (1).

$$n = \frac{R_x}{R_s} \quad (1)$$

When comparing AC and DC resistance bridges, AC bridges are simpler to construct and in so bare a lower price. Also DC bridges are easier to evaluate since they only have one component of uncertainty, whereas AC bridges have a real and an imaginary component of uncertainty. However AC bridges are faster in measurement, since they do not need to change the current direction as do DC bridges, to compensate for thermal voltages. Currently the most used DC bridges are the MI6010T, the MI6015T and the Guildline 6675, the mostly used AC bridges are the ASL F700, F18 and F900.

To assure that measurements are being made with the lowest possible uncertainty, both types of instruments have to be regularly checked for correct operation. In both types of instruments the most contributing factor of uncertainty comes from their non-linearity. With classic instruments this is mainly due to the non-linearity of the AD converter and with resistance bridges due to the non-linearity or incorrect behaviour of the ratio transformer. If the non-linearity of an instrument is assessed, its correct operation and uncertainty can be determined. The most convenient and most extensive way to do this is the use of a resistance bridge calibrator (RBC) [1] [2] [3]. The RBC is a passive device, which is based on 4 stable resistors that can be connected in parallel and serial connections to generate 35 different resistances. Because these 35 resistances are based on the 4 stable resistors, a comparison of the calculated and measured values provides an evaluation of the non-linearity for the instrument under test.

In this paper the repeatable and reproducible evaluation of several resistance measurement instruments will be presented. The tested instruments are mainly used in laboratory conditions for temperature measurement. The evaluations of the instruments non-linearity will be performed by use of an automated resistance bridge calibrator.

## 2. RESISTANCE BRIDGE CALIBRATOR RBC100



Fig. 1. Resistance bridge calibrator RBC100.

The resistance bridge calibrator RBC100 (Fig. 1) is a simple passive electrical circuit, which consists of four base resistors that can be connected in various serial and parallel combinations [4] [5]. In this way, different resistance values can be realized. These values are fully defined by values of the four base resistors. All connections to the resistors are 4 wire type which eliminates the influence of connector wire resistances. The RBC 100 is able to realize 35 different resistances in the range from 16.9 to 129.9  $\Omega$ .

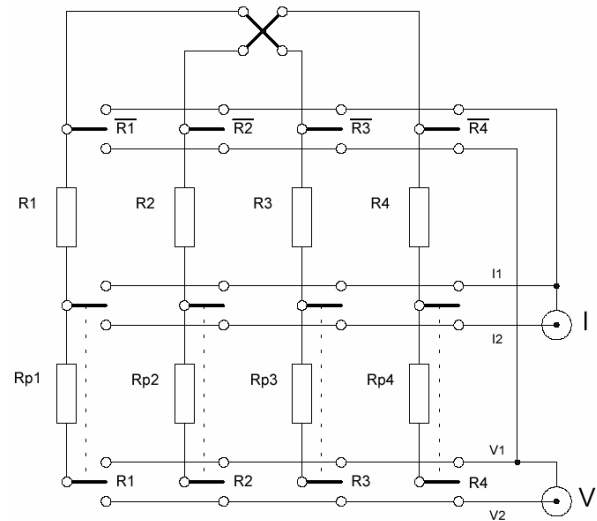


Fig. 2. RBC schematic.

The circuit schematic for the RBC is shown in Fig. 2. On the front panel of the calibrator, there are eight three-position switches, which switch the base resistors (in Fig. 2 marked  $R_1$  to  $R_4$ ) into different serial and parallel combinations. Besides the four base resistors there are also four potential sharing resistors (in Fig. 2 marked  $R_{p1}$  to  $R_{p4}$ ) which compensate the voltage drops on the connector wires to the base resistor when two or more are connected in parallel. The values of the potential sharing resistors are proportional to the values of the base resistors; values for both are given in Table 1.

Table 1. Values of base and potential sharing resistors used in the RBC100.

	Base resistor	Pot. sh. resistor
1	81,8186 $\Omega$	2,6327 $\Omega$
2	48,1768 $\Omega$	1,5495 $\Omega$
3	36,5153 $\Omega$	1,1749 $\Omega$
4	31,2419 $\Omega$	1,0049 $\Omega$

The RBC100 is mainly intended to evaluate the nonlinearity of resistance bridges used in combination with 25 ohm 100 ohm standard resistors. However it can also be used to determine the nonlinearity of other resistance instruments that measure resistance in the range of SPRTs (10 to 120 ohms).

## 3. AUTOMATION OF THE RBC100

The RBC100 is a manually operated device. Testing several instruments would make the task a tedious one and thus the device was automated. The main reasons for automation were:

- switching of the RBC100 takes a large amount of time when an operator needs to be present; the measuring of all 35 combinations may take up to 9

hours on some resistance bridges. By automating the device, the need for an operator is eliminated. This also means that measurements can be done when the instrument under test is not being used and no personnel are present (during nights and weekends).

- Although the resistors used inside of the RBC100 are of the good quality, they still show temperature dependence. Because of this the measurements done with the RBC100 are not repeatable below 0.1 ppm, when used in an environment with temperature stability of  $\pm 1^\circ\text{C}$ . To solve this problem, the RBC100 needs to be inserted in a temperature stable environment (temperature chamber), which then requires tele-operation from outside.
- Automating the RBC100 enables the measurements to be automatically acquired and processed.

The process of automation was divided into three steps. In the first step a manipulator unit was created, which is responsible for the movement of the switches on the calibrator. The manipulator unit is built around an aluminum L-frame attached on the calibrator itself. Eight small servomotors are mounted into the L-frame, these move the switches of the calibrator using semi-rigid mechanical links (Fig. 3). The servomotors were chosen in such a way that the force they produce cannot mechanically harm the switches on the RBC100.



Fig. 3. Manipulator unit on top of RBC100.

During the second step a purpose designed controller was created. The controller communicates to the PC using an RS232 interface. The commands received from the PC are transformed inside the controller to PWM signals that control the servomotors of the manipulator unit. The controller also incorporates the power supply for the servomotors.

In the last step a computer application was created that controls the whole calibration process. This application enables the setting of parameters of the manipulator unit (end-points for the movement of every switch), it acquires the measurements from the instrument under test and calculates the non-linearity and associated standard deviation (Fig. 4).

The automation process is described in detail in [6] [7].

Along with the automation of the manual RBC, a completely automatic RBC was created. This uses relays instead of toggle switches. The electric schematic is similar to the schematic of the manual RBC, it also uses the same computer application to control the calibration process. Due to a lower quality of the components used to construct it, the automatic unit is only capable of measuring non-linearity down to 1 ppm. Since the requirement was to measure the non-linearity in the ranges down to 0.02 ppm, only the automated RBC100 was used.

The detailed description of construction of the completely automatic RBC is available in [8].

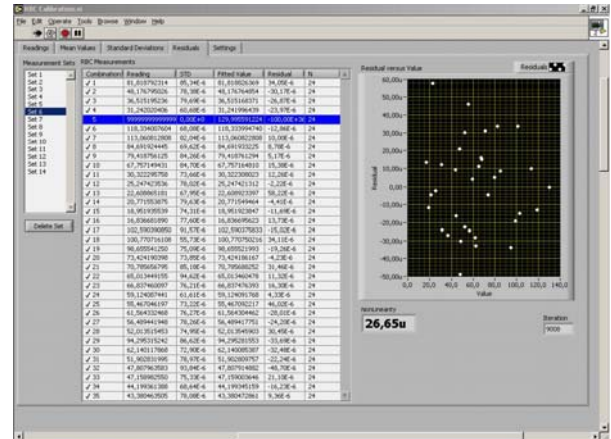


Fig. 4. Program window of the computer application.

#### 4. MEASUREMENTS

The non-linearity tests were performed on seven instruments that measure resistance. All the tested instruments are being used in conjunction with platinum resistance thermometers to measure temperature at the Laboratory of Metrology and Quality, Faculty of electrical engineering, Ljubljana, Slovenia. Tested were the following instruments:

- HP34401A multimeter (not calibrated), declared uncertainty in the range from 0 to 120  $\Omega$  equal to 60 ppm (6 m $\Omega$ ) [9]
- HP3458A multimeter (not calibrated) and the newer Agilent 3458 multimeter (calibrated previously, SIQ), declared uncertainty in the range from 0 to 120  $\Omega$  equal to 6ppm (0.6 m $\Omega$ ) [9]
- HP34420A Nano-volt-/micro-ohmmeter (not calibrated), declared uncertainty in the range from 0 to 120  $\Omega$  equal to 17 ppm (1.7 m $\Omega$ ) [9]
- ASL F700 AC bridge declared uncertainty 1ppm, ratio measurement from 0 to 4, used with temperature stabilized standard 100  $\Omega$  resistor [10]
- MI6010T DC bridge, declared uncertainty 0.05 ppm, ratio measurement from 0 to 13, used with a Tinsley 5685 (25  $\Omega$ ) standard resistor that is temperature stabilized in an oil bath [11] [12]
- ASL F900 AC bridge declared uncertainty 0.02ppm, ratio measurement from 0 to 1.3, used

with a Tinsley 5685 (100  $\Omega$ ) standard resistor that is temperature stabilized in an oil bath [10] [12]

The equipment used to determine the non-linearity of the instruments under test (Fig. 5), consisted of the RBC100 inside a temperature stable environment (Styrofoam enclosure with temperature stability of  $\pm 0.1$   $^{\circ}\text{C}$ ), the automation controller and a personal computer (notebook) running the purposely designed computer application. All the tests were done in laboratory conditions, with a temperature of 23 $^{\circ}\text{C}$  stable to  $\pm 1$   $^{\circ}\text{C}$ .

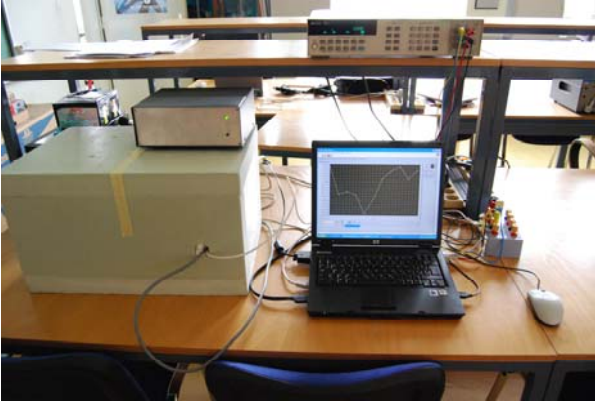


Fig. 5. Automated non-linearity testing of HP3458A multimeter.

Testing of the instruments was conducted in two rounds of measurements. During each round three sets were measured with each instrument (instruments were interchanged and measured until every instrument was tested, the process was then repeated during the second round). The measurement current for the resistance bridges was set to 1 mA, it being equal to the measuring current of the multimeters. This ensured a level of comparison for all of the instruments under test. During each set all of the 35 RBC100 combinations (resistance values) were measured. For each combination 60 readings were taken and averaged to give one measurement. The readings were taken every 15 s with the ASL F900 bridge, every 10 s with the MI6010T bridge, every 2 s with the ASL F700 bridge and every 3 s with other instruments. The time to measure one set took from 70 minutes with the ASL F700 up to around 9 hours for the ASL F900. From the 60 readings that were taken for every combination, 30 were discarded to eliminate any transition effects between combinations (present mostly with resistance bridges). From the remaining 30 readings the average value and standard deviation were calculated. These were then used in the program application to calculate the non-linearity and the associated standard deviation of the instrument under test.

Results of the non-linearity tests are presented in Table 2. The combination with the value of 129.9  $\Omega$  was not used with the ASL F900 and multimeter-type instruments, since its value was out of range for these particular instruments (range limit for the ASL F900).

Table 2. Type size for manuscript (in points).

Instrument	1 <sup>st</sup> set:	2 <sup>nd</sup> set:	3 <sup>rd</sup> set:
	Round 1 Round 2	Round 1 Round 2	Round 1 Round 2
HP34401A	380 $\mu\Omega$ 374 $\mu\Omega$	361 $\mu\Omega$ 388 $\mu\Omega$	362 $\mu\Omega$ 366 $\mu\Omega$
HP34420A	27 $\mu\Omega$ 22 $\mu\Omega$	18 $\mu\Omega$ 25 $\mu\Omega$	21 $\mu\Omega$ 24 $\mu\Omega$
HP3458A (neumerjen)	24 $\mu\Omega$ 19 $\mu\Omega$	24 $\mu\Omega$ 23 $\mu\Omega$	22 $\mu\Omega$ 22 $\mu\Omega$
AGILENT 3458A (umerjen)	23 $\mu\Omega$ 24 $\mu\Omega$	26 $\mu\Omega$ 27 $\mu\Omega$	27 $\mu\Omega$ 28 $\mu\Omega$
ASL F700	0.465 ppm 0.570 ppm	0.484 ppm 0.484 ppm	0.459 ppm 0.497 ppm
MI 6010T	0.047 ppm 0.046 ppm	0.049 ppm 0.050 ppm	0.046 ppm 0.049 ppm
ASL F900	0.025 ppm 0.027 ppm	0.024 ppm 0.025 ppm	0.030 ppm 0.028 ppm

The results of the non-linearity tests showed that the nonlinearity for multimeter-type instruments was much lower than the stated uncertainty. The reasons for this are:

- Non-linearity in a multimeter-type instrument is an influential parameter on the uncertainty, however it is not a dominant one
- measurements were done in a laboratory environment with a stable temperature; the uncertainty of the instrument is given for a temperature range between -20 and 40  $^{\circ}\text{C}$ . The laboratory environment hence made the instrument to behave at its best

With a prior calibration of a resistance thermometer and a multimeter-type instrument as a system, the systems uncertainty could be brought down to the level of the nonlinearity of the instrument.

In the case of resistance bridges, it appears that the non-linearity of the bridge, due to the non linearity of the ratio transformer, proves to be the dominant factor and in so the two numbers are similar. The results of non-linearity testing of the resistance bridges are given in ppm (part-per-million), since resistance bridges do not measure resistance directly, but measure a ratio between an unknown resistor (thermometer) and a standard resistor. The non-linearities converted to  $\mu\Omega$  are for the tested resistance bridges equal to:

- 50  $\mu\Omega$  for the ASL F700 resistance bridge
- 5  $\mu\Omega$  for the MI6010T resistance bridge
- 3  $\mu\Omega$  for the ASL F900 resistance bridge

The non-linearity tests performed on the ASL F700 and the MI6010T (calculated to  $\mu\Omega$ ) would have shown better results, however standard resistors limited the measuring range to one third of the ASL F700 and one half of MI6010T, and in so increased the non-linearity value calculated in  $\mu\Omega$ .

The non-linearities for all the instruments, except for the ASL F900, were within their declared values. With the ASL F900 the used RBC100 was at its limit of uncertainty and in so this result is a combination of the non-linearity of the ASL F900 and uncertainty of RBC100.



#### 4. CONCLUSION

Within the scope of this paper, the successful non-linearity testing of seven instruments that measure resistance has been performed. The non-linearity tests were performed in the range from 16.9 to 129.9  $\Omega$ . For the four multimeter-type instruments (using the UI-method) the values were much lower than the declared uncertainty and these values give credible information on the quality of AD converters inside the instruments. With the resistance bridges, their non-linearity proved to be the dominant factor in their uncertainty. With all the instruments the measured non-linearity was within the declared values, which showed that all the instruments are measuring correctly.

The tests were done in two consecutive rounds, during which each instrument was tested. The gathered results proved to be repeatable (between sets within one round) and reproducible (between rounds when an instrument has been disconnected and again connected for repeated testing).

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