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Coherence of comparison results obtained by new inductance comparator bridge

***Abstract**. Few years ago a high-precision multi-range comparator bridge KWL5 was constructed at Silesian University of Technology, Gliwice, Poland. The instrument enables 1:1 comparison of inductors from 100 μH to 10 H in the frequency range from 100 Hz to 10 kHz with the smallest uncertainty possible. Results of a coherence test performed for this instrument are presented here. The coherence investigation, commonly called the "triangle method", is a effective way to prove the lack of a most systematic errors and large random errors in the measurement procedure realized by the instrument.*

***Streszczenie.** Kilka lat temu w Instytucie Metrologii, Elektroniki I Automatyki Politechniki Śląskiej w Gliwicach zaprojektowano i zbudowano precyzyjny wielozakresowy komparator wzorców indukcyjności KWL5. Przyrząd służy do komparacji wzorców indukcyjności o jednakowych wartościach nominalnych od 100 μH do 10 H w zakresie częstotliwości od 100 Hz do 10 kHz. W artykule przedstawiono metodę badań i wyniki spójności wyników komparacji wykonanych komparatorem KWL5. Spójne wyniki komparacji świadczą o braku błędów systematycznych i większych błędów przypadkowych podczas procedury pomiarowej. (**Spójność wyników komparacji uzyskanych nowym, wielozakresowym komparatorem impedancji**).*

Keywords: coherence test, impedance comparator bridge, inductance measurements, inductance standard.
Słowa kluczowe: badanie spójności, komparator impedancji, pomiar indukcyjności, wzorzec indukcyjności.

Introduction

Several years ago self-balancing comparator bridges for maintenance of inductance standard (called KWL2, KWL3 and KWL4) were constructed by a research team from Silesian University of Technology, Gliwice, Poland exclusively for the comparison of 10 mH inductance standards at frequencies 1 kHz and 1592 Hz [1]. The three bridges define the standards under comparison as two-terminal-pair (2TP) impedances and differ one to the other in the digital part, but the principle of measurement, based on the unbalanced transformer bridge, is the same for all instruments. The coherence test for the KWL3 bridge was performed [2]. Nowadays, the bridges KWL2 and KWL3 are used at the Central Office of Measures (GUM) in Warsaw, Poland, and at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, to compare the standards of the group with the standard defined by means of the M-W bridge, or for intercomparisons. A digitally controlled switch was constructed to perform the intercomparison process automatically [3].

Most NMIs maintain the inductance unit and perform calibration for customers exclusively based on two-terminal (2T) or three-terminal (3T) standards and measurement arrangements. While for ac resistors and capacitors a four-terminal-pair (4TP) standard definition is commonplace and 4TP commercial measurement systems are available on the market, for inductors a two- or three-terminal definition is still the most common. It is probable that this scenario will change in the future. At the NMI level, the accuracy and frequency range of inductance measurements is steadily increasing; hence, a 4TP definition becomes increasingly appealing [4], [5]. Therefore, the new KWL5 multi-range bridge, which we constructed, defines the standard under comparison as four-terminal-pair impedances. The unbalance transformer bridge enables the direct measurement of differences of both impedance components (ΔL and ΔR). The bridge is suitable for comparing inductance standards from 100 μH to 10 H in a wide frequency range and is convenient for automatic operation.

Checking the coherence of the comparison results obtained by the instrument being tested prove to be a very effective way of testing comparator bridges. Obtaining a coherent series of results during comparison of standards proves the lack of most systematic errors and large random errors in the measurement procedure realized automatically by the instrument.

Comparator bridge KWL5

The scatter of the characteristics of the 1482 type inductance standards, most often met at NMIs, were taken as a base for the project of a new KWL5 instrument. Due to the assumed wide range of nominal inductance values (from 100 μH to 10 H) and wide frequency range (100 Hz – 10 kHz), the impedances being compared cover the range between 62 mΩ (for 100 μH and 100 Hz) and 628 kΩ (for 10H and 10 kHz). It is obvious that when small impedances are compared, inevitable stray inductances should be taken into consideration. These include inductances of the leads and the connections. To reduce these influences the comparison should be performed using 4-wire technique. Therefore, the circuit diagram was modified to extend the impedance range and it has a structure similar to the Kelvin double bridge, commonly used for DC measurements of small resistance (Fig. 1).

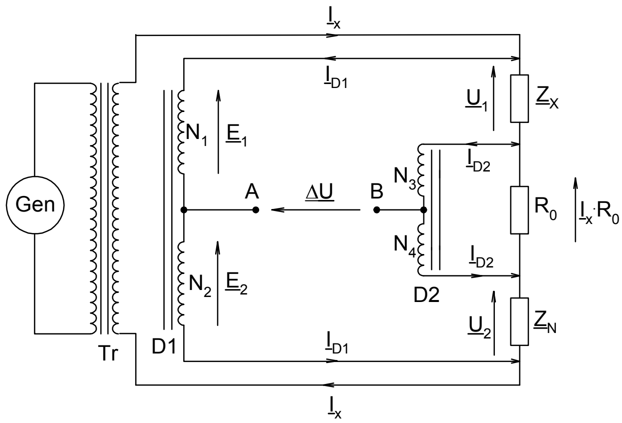

Fig. 1. Principal circuit diagram of the KWL5 bridge

When the same current $\underline{I}_x$ flows through the impedances $\underline{Z}_x$ and $\underline{Z}_N$ and turn ratios of the autotransformers D1 and D2 are denoted by:

$$n=\frac{N_1}{N_2},\quad m=\frac{N_3}{N_4},\tag{1}$$

than, using the Kirchhoff's voltage law, the following equation describing the circuit can be written:

$$2\underline{\Delta U}=\frac{\underline{I}_X\,R_0(n-1)}{n+1}-\frac{\underline{I}_X\,R_0(m-1)}{m+1}+\frac{2(\underline{U}_1-n\underline{U}_2)}{n+1}.\tag{2}$$

If the turn ratios of the D1 and D2 are equal ($m = n$) the above equation simplifies to the form:

(3) $$2\underline{\Delta U} = \frac{2(\underline{U}_1 - n\underline{U}_2)}{n+1}.$$

Since

(4) $$\underline{U}_1 = \underline{Z}_X \underline{I}_X, \quad \underline{U}_2 = \underline{Z}_N \underline{I}_X$$

and the number of turns $N_1 = N_2 = N_3 = N_4$ ($n = m = 1$), therefore (4) has the same form as equation given for the bridge KWL3 [5]:

(5) $$\underline{Z}_X - \underline{Z}_N = \frac{2\underline{\Delta U}}{\underline{I}_X}.$$

Hence, the KWL5 four-terminal circuit has the same advantage as the two-terminal KWL4: direct measurement of the inductance and series resistance differences of compared inductors, and furthermore it enables comparing small impedances. In the modified circuit impedances of leads and connections have no influence on the unbalance voltage $\underline{\Delta U}$. The voltage depends only on the difference of the compared impedances and the measuring current $\underline{I}_X$.
Since

(6) $$\underline{\Delta U}_0 = R_0 \underline{I}_X$$

hence equation (5) can be expressed as:

(7) $$\underline{\Delta Z} = \underline{Z}_X - \underline{Z}_N = \frac{2\underline{\Delta U} R_0}{\underline{\Delta U}_0}$$

Finally the components of the impedance difference ΔL and ΔR are calculated from the following formulas:

(8) $$\Delta R = \mathrm{Re}\left\{\frac{2\underline{\Delta U} R_0}{\underline{\Delta U}_0}\right\} = 2R_0 \frac{\mathrm{Re}\{\underline{\Delta U}\}\mathrm{Re}\{\underline{\Delta U}_0\} + \mathrm{Im}\{\underline{\Delta U}_0\}\mathrm{Im}\{\underline{\Delta U}_0\}}{\mathrm{Re}^2\{\underline{\Delta U}_0\} + \mathrm{Im}^2\{\underline{\Delta U}_0\}}$$

(9) $$\Delta L = \frac{1}{\omega}\mathrm{Im}\left\{\frac{2\underline{\Delta U} R_0}{\underline{\Delta U}_0}\right\} = \frac{2R_0}{\omega}\cdot\frac{\mathrm{Im}\{\underline{\Delta U}\}\mathrm{Re}\{\underline{\Delta U}_0\} - \mathrm{Re}\{\underline{\Delta U}\}\mathrm{Im}\{\underline{\Delta U}_0\}}{\mathrm{Re}^2\{\underline{\Delta U}_0\} + \mathrm{Im}^2\{\underline{\Delta U}_0\}}$$

and the comparison result is displayed on the LCD panel of the KWL5 bridge (Fig.2).

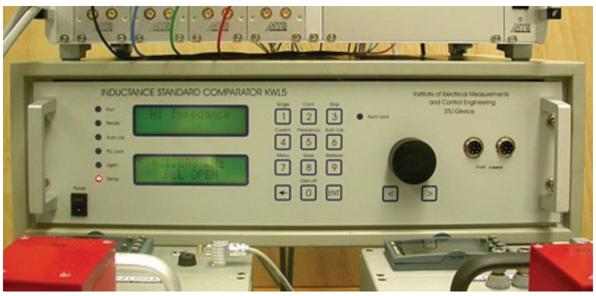

Fig. 2. Front view of the KWL5 bridge

Coherence of comparison results

In order to eliminate systematic errors cause by the measuring circuit (e.g. impedance differences of the bridge channels, cables and connections) the measurement of impedance difference are usually performed twice by interchanging the standards compared S_i and S_j in positions (Fig. 3). First, the standard S_i is connected to the Input A and the standard S_j is connected to the Input B. Thereafter, the standards are interchanged in positions and the standard S_j is connected to the Input A. The final result of impedance difference is calculated as average value of the two raw results.

For checking a coherence of comparison results obtained by the instrument being tested a group consisted of three standards is appropriate. If we consider the comparison scheme shown in Fig. 4 we obtain six differences (as row results of measurement) which can be expressed by the following equations

(10)
$$\Delta S_{12} = S_1 - S_2,$$
$$\Delta S_{21} = S_2 - S_1,$$
$$\Delta S_{13} = S_1 - S_3,$$
$$\Delta S_{31} = S_3 - S_1,$$
$$\Delta S_{23} = S_2 - S_3,$$
$$\Delta S_{32} = S_3 - S_2,$$

where variable "S" represents inductance "L" or resistance "R", depending on which component is measured.

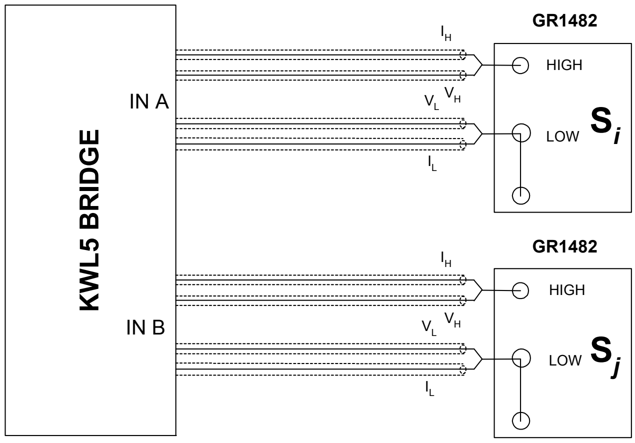

Fig. 3. Connection of standards to the KWL5 bridge (i, j = 1, 2, 3 and $i \neq j$)

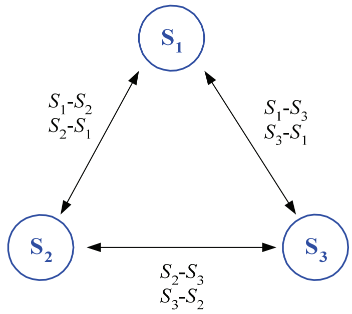

Fig. 4. Comparison scheme for a group consisted of 3 standards

The comparison scheme shown in Fig. 4 can be extended for any number of standards and then set of equations (10) can be described by the formula

(11) $$\Delta S_{ij} = S_i - S_j;\ i \neq j.$$

Let's notice that in a perfect circuit two differences ΔS_{ij} and ΔS_{ji}, obtained by the interchange procedure, have the same absolute value but opposite signs. However, in a real measuring circuit the impedance of the bridge channels and cables cause systematic error, so the equations set (10) should be written in the following form

(12)
$$\Delta S_{12} = S_1 - S_2 + \Delta S,$$
$$\Delta S_{21} = S_2 - S_1 + \Delta S,$$
$$\Delta S_{13} = S_1 - S_3 + \Delta S,$$
$$\Delta S_{31} = S_3 - S_1 + \Delta S,$$
$$\Delta S_{23} = S_2 - S_3 + \Delta S,$$
$$\Delta S_{32} = S_3 - S_2 + \Delta S.$$

When we calculate difference of each corresponding pair of results and divide the difference by two, then we obtain the corrected results of impedance differences

(13) $$\Delta S_{12C} = \frac{\Delta S_{12} - \Delta S_{21}}{2} = S_1 - S_2,$$

(14) $$\Delta S_{13C} = \frac{\Delta S_{13} - \Delta S_{31}}{2} = S_1 - S_3,$$

(15) $$\Delta S_{23\mathrm{C}} = \frac{\Delta S_{23} - \Delta S_{32}}{2} = S_2 - S_3 .$$

It can be seen, that the influence of unequal series impedances of the measuring channels is eliminated by the interchange procedure. Hence, the final results of impedance differences should be calculated as half of difference of the two raw results ΔS_{ij} and ΔS_{ji}.

The “triangle method”, presented here, consists in checking the sum of Eqs. (13) to (15). For a perfect measuring instrument and perfect circuit, the sum of the equations should give the zero (the triangle in Fig. 4 is then closed)

(16) $$\left|\Delta S_{12\mathrm{C}} + \Delta S_{13\mathrm{C}} + \Delta S_{23\mathrm{C}}\right| = 0 .$$

However, in practice the sum in usually non-zero because of imperfection of the measuring instrument and circuit. So we have to allow for some small difference for which we can assume that equation (16) is satisfy enough accurate. This maximum allowed difference will be sign further as λ and will be called the level of coherence of comparison results. Taking the above into consideration we can write that all results of measurements should satisfy the coherence principle

(17) $$\left|\Delta S_{12\mathrm{C}} + \Delta S_{13\mathrm{C}} + \Delta S_{23\mathrm{C}}\right| \le \lambda .$$

The λ is arbitrary assumed level of coherence (e.g. λ = 5 nH i.e. 0.5 ppm for 10 mH standards compared). If the results of measurements don’t satisfy equation (17), then the coherence principle isn’t satisfied (i.e. series of measurement isn’t coherent). It proves, that some systematic errors or large random errors in the measuring circuit affect the comparison results.

Testing

The new KWL5 multi-range bridge for inductance standard calibration was preliminary tested in October 2005 at the PTB in Braunschweig. Then the coherence test based on checking the formula (18) was performed. For this purpose, the relevant differences of inductance and resistance ΔL_{ij}, ΔL_{ji}, ΔR_{ij} and ΔR_{ji} were measured for each pair of standards and afterward, the corrected results were calculated.

The coherence tests were done for three groups of standards (100 μH group, 10 mH group and 1 H group) and it helped the constructors of the KWL5 bridge to improve the instrument. Each group consisted of three standard inductors of different inductance, resistance and factor values. Only in such case, the coherence test is a powerful tool to prove the lack of most systematic errors and large random errors in the measurement procedure realized automatically by the instrument. The comparisons was performed at different frequencies (within the range 100 Hz – 10 kHz) and at different measuring currents (from 130 μA to 10 mA). The standards were compared using the KWL5 bridge as shown in Fig. 3. The comparison results for the 100 μH, 10 mH and 1 H group are shown in Tables 1, 3 and 5, respectively. In these tables only measurements at two frequencies are shown. For each group the worst and the best case are presented. In Tables 2, 4 and 6 the calculations are shown. The sums of calculated differences placed in the last row of Tables 2, 4 and 6 correspond to the level of coherence of the comparison results. When we refer these level of coherence to the nominal value of the compared standards and multiply the ratio by million, than the level of coherence will be expressed in ppm.

As we can see in Table 2, for 100 μH standards the best result of inductance coherence level was achieved at 400 Hz (0 ppm) and the worst at 4 kHz (23 ppm). For 10 mH group (Table 4) the highest coherence was obtained at 500 Hz (0.5 ppm) and the lowest (9.2 ppm) at 4 kHz. When 1 H standards were compared then the best result of inductance coherence equal to 7.8 ppm (at 100 Hz) and the worst was 22.7 ppm (at 2 kHz). Generally, observing presented data and considering also other results (ommited in the paper) the worst coherence level (above 10 ppm) was obtained at high frequency (≥2kHz). At frequencies from 100 Hz to 500 Hz the results of coherence were usually the best. This information was very useful for constructors and helped him to improve the designed instrument.

Table 1. Results of first coherence test for 100 μH group (S_1: impedance of standard GR1482B No.13827, S_2: impedance of standard GR1482B No.19152, S_3: impedance of standard GR1482B No.20818)

Impedance connected to bridge input		Measured difference	Comparison results ΔL_{ij} [μH]		Comparison results ΔR_{ij} [mΩ]	
Input A	Input B		f = 400 Hz I_x =10mA	f = 4 kHz I_x =10mA	f = 400 Hz I_x =10mA	f = 4 kHz I_x =10mA
S_1	S_2	$\Delta S_{12} = S_1 - S_2$	-0.0717	-0.0590	-17.2200	-17.1000
S_2	S_1	$\Delta S_{21} = S_2 - S_1$	0.0500	0.0530	17.2100	17.5183
S_2	S_3	$\Delta S_{23} = S_2 - S_3$	0.0517	0.0437	-1.3267	-0.6867
S_3	S_2	$\Delta S_{32} = S_3 - S_2$	-0.0767	-0.0492	0.7733	1.1467
S_3	S_1	$\Delta S_{31} = S_3 - S_1$	-0.0100	0.0055	18.2517	18.4467
S_1	S_3	$\Delta S_{13} = S_1 - S_3$	-0.0033	-0.0090	-18.0500	-18.5667

Table 2. Coherence calculations for results inserted in Table 1

Formula	Calculation results ΔL_{ijC} [μH]		Calculation results ΔR_{ijC} [mΩ]	
	f = 400Hz	f=4 kHz	f = 400Hz	f=4 kHz
$\Delta S_{12C} = 0.5(\Delta S_{12} - \Delta S_{21})$	-0.061	-0.0560	-17.22	-17.3092
$\Delta S_{23C} = 0.5(\Delta S_{23} - \Delta S_{32})$	0.064	0.0464	-1.05	-0.9167
$\Delta S_{31C} = 0.5(\Delta S_{31} - \Delta S_{13})$	-0.003	0.0073	18.15	18.5067
|SUM|	**0.000**	**0.023**	**0.12**	**0.2808**

Table. 3. Results of first coherence test for 10 mH group (S_1: impedance of standard GR1482H No.4665, S_2: impedance of standard GR1482H No.4865, S_3: impedance of standard GR1482H No.4866)

Impedance connected to bridge input		Measured difference	Comparison results ΔL_{ij} [μH]		Comparison results ΔR_{ij} [mΩ]	
Input A	Input B		f = 4 kHz I_x =2.5mA	f = 500Hz I_x =2.5mA	f = 100 Hz I_x =2.5mA	f = 500Hz I_x=2.5mA
S_1	S_2	$\Delta S_{12} = S_1 - S_2$	-4.39	1.74	-290.77	-294.26
S_2	S_1	$\Delta S_{21} = S_2 - S_1$	5.24	-0.13	290.64	289.23
S_2	S_3	$\Delta S_{23} = S_2 - S_3$	7.61	5.17	150.51	149.73
S_3	S_2	$\Delta S_{32} = S_3 - S_2$	-7.19	-3.58	-150.81	-154.59
S_3	S_1	$\Delta S_{31} = S_3 - S_1$	-2.26	-4.51	139.04	136.78
S_1	S_3	$\Delta S_{13} = S_1 - S_3$	2.73	6,11	-140,137	-141,92

Table 4. Coherence calculations for results inserted in Table 3

Formula	Calculation results ΔL_{ijC} [μH]		Calculation results ΔR_{ijC} [mΩ]	
	f = 4 kHz	f=500Hz	f = 100Hz	f=500Hz
$\Delta S_{12C} = 0.5(\Delta S_{12} - \Delta S_{21})$	-4.813	0.935	-290.71	-291.75
$\Delta S_{23C} = 0.5(\Delta S_{23} - \Delta S_{32})$	7.400	4.373	150.66	152.16
$\Delta S_{31C} = 0.5(\Delta S_{31} - \Delta S_{13})$	-2.495	-5.313	139.59	139.35
|SUM|	**0.092**	**0.005**	**0.46**	**0.23**

Table. 5. Results of first coherence test for 1 H group (S_1: impedance of standard GR1482P No.19051, S_2: impedance of standard GR1482P No.20713 S_3: impedance of standard GR1482P No.18437)

Impedance connected to bridge input		Measured difference	Comparison results ΔL_{ij} [μH]		Comparison results ΔR_{ij} [mΩ]	
Input A	Input B		f = 100 Hz I_x =130μA	f = 2kHz I_x =130μA	f = 100 Hz I_x =130μA	f = 2kHz I_x =130μA
S_1	S_2	$\Delta S_{12} = S_1 - S_2$	-576.6	-650.71	-2094.3	-5128.8
S_2	S_1	$\Delta S_{21} = S_2 - S_1$	673.0	210.905	2057.3	5893.33
S_2	S_3	$\Delta S_{23} = S_2 - S_3$	-351.6	205.27	-3396.4	-26403.2
S_3	S_2	$\Delta S_{32} = S_3 - S_2$	338.5	302.625	3296.1	26680.2
S_3	S_1	$\Delta S_{31} = S_3 - S_1$	912.7	731.00	5551.2	31999.2
S_1	S_3	$\Delta S_{13} = S_1 - S_3$	-1011.3	-182.478	-5594.9	-31799.2

Table 6. Coherence calculations for results inserted in Table 5

Formula	Calculation results ΔL_{ijC} [μH]		Calculation results ΔR_{ijC} [mΩ]	
	f = 100Hz	f=2 kHz	f = 100Hz	f=2 kHz
$\Delta S_{12C} = 0.5(\Delta S_{12} - \Delta S_{21})$	-624.767	-430.809	-2075.79	-5511.08
$\Delta S_{23C} = 0.5(\Delta S_{23} - \Delta S_{32})$	-345.050	-48.676	-3346.28	-26541.67
$\Delta S_{31C} = 0.5(\Delta S_{31} - \Delta S_{13})$	961.992	456.737	5573.02	31899.17
|SUM|	**7.825**	**22.748**	**150.94**	**153.58**

Table 7. Results of differences measurements for group consisted of three 1 mH standards (S_1 – impedance of standard GR1482E No. 18473, S_2 – impedance of standard GR1482E No.18460, S_3 impedance of standard QT1482E No. 5500219)

Impedance connected to bridge input		Measured difference	Comparison results ΔL_{ij} [μH]		Comparison results ΔR_{ij} [mΩ]	
Input A	Input B		f = 1 kHz I_x =5mA	f = 10kHz I_x =5mA	f = 1 kHz I_x =5mA	f = 10kHz I_x =5mA
S_1	S_2	$\Delta S_{12} = S_1 - S_2$	0.773	0.068	-2.1	1.1
S_2	S_1	$\Delta S_{21} = S_2 - S_1$	-0.783	-0.682	3.4	0.1
S_2	S_3	$\Delta S_{23} = S_2 - S_3$	-0.731	-0.215	-18.0	-21.2
S_3	S_2	$\Delta S_{32} = S_3 - S_2$	0.722	0.198	19.6	22.2
S_3	S_1	$\Delta S_{31} = S_3 - S_1$	-0.054	-0.479	22.3	21.8
S_1	S_3	$\Delta S_{13} = S_1 - S_3$	0.046	0.465	-20.6	-20.5

Table 8. Coherence calculations for results inserted in Table 7

Formula	Calculation results ΔL_{ijC} [μH]		Calculation results ΔR_{ijC} [mΩ]	
	f = 1 kHz	f=10 kHz	f = 1 kHz	f=10 kHz
$\Delta S_{12C} = 0.5(\Delta S_{12} - \Delta S_{21})$	0.778	0.675	-2.75	0.50
$\Delta S_{23C} = 0.5(\Delta S_{23} - \Delta S_{32})$	-0.727	-0.207	-18.8	-21.70
$\Delta S_{31C} = 0.5(\Delta S_{31} - \Delta S_{13})$	-0.050	-0.472	21.45	21.15
|SUM|	**0.002**	**0.003**	**0.10**	**0.05**

Table 9. Results of differences measurements for group consisted of three 10 mH standards (S_1 – impedance of standard GR1482H No.17864, S_2 – impedance of standard GR1482H No. 17862, S_3 – impedance of standard GR1482H No. 17859)

Impedance connected to bridge input		Measured difference	Comparison results ΔL_{ij} [μH]		Comparison results ΔR_{ij} [mΩ]	
Input A	Input B		f = 1 kHz I_x =2.5mA	f = 10kHz I_x =0.5mA	f = 1 kHz I_x =2.5mA	f = 10kHz I_x =0.5mA
S_1	S_2	$\Delta S_{12} = S_1 - S_2$	4.548	1.71	-144.3	-132
S_2	S_1	$\Delta S_{21} = S_2 - S_1$	-4.563	-1.98	145.6	198
S_2	S_3	$\Delta S_{23} = S_2 - S_3$	-1.048	-0.14	-202.0	-193
S_3	S_2	$\Delta S_{32} = S_3 - S_2$	1.030	-0.10	203.0	253
S_3	S_1	$\Delta S_{31} = S_3 - S_1$	-3.524	-1.96	348.1	420
S_1	S_3	$\Delta S_{13} = S_1 - S_3$	3.504	1.70	-347.0	-361

Table 10. Coherence calculations for results inserted in Table 9

Formula	Calculation results ΔL_{ijC} [μH]		Calculation results ΔR_{ijC} [mΩ]	
	f = 1 kHz	f=10 kHz	f = 1 kHz	f=10 kHz
$\Delta S_{12C} = 0.5(\Delta S_{12} - \Delta S_{21})$	4,556	1.845	-144.95	-165
$\Delta S_{23C} = 0.5(\Delta S_{23} - \Delta S_{32})$	-1.039	-0.020	-202.50	-223
$\Delta S_{31C} = 0.5(\Delta S_{31} - \Delta S_{13})$	-3.514	-1.830	347.55	390.5
|SUM|	**0.002**	**0.005**	**0.10**	**2.5**

The further coherence investigation of comparison results was performed for 1 mH and 10 mH GenRad type standard inductors at 1 kHz and 10 kHz and at different values of measuring current. The measurements were performed in July 2007 in Laboratory of Inductance and Capacitance Measurements at the PTB (Braunschweig, Germany). The standards were compared using improved KWL5 bridge. Modification of the bridge concerned high frequency properties and digital part improving. Results of differences measurements for inductance and resistance were inserted in Tables 7 and 9. In Tables 8 and 10 the calculation results for ΔL_{12C}, ΔL_{23C}, ΔL_{31C}, ΔR_{12C}, ΔR_{23C}, ΔR_{31C} were inserted. The sums of calculated differences placed in the last row of Tables 8 and 10 correspond to the level of coherence of the comparison results.

It can be seen that for 1 mH group the coherence level is 2 ppm at 1 kHz and 3 ppm at 10 kHz. Moreover, for 10 mH group the result of coherence is smaller than 1 ppm (0.2 ppm at 1 kHz and 0.5 ppm at 10 kHz). The coherence level obtained for resistance differences after improvement of the bridge is also significantly better than before. The worst result after improvement was obtained for 10 mH standards at 10 kHz and was equal to 0,03%, whereas the worst result of coherence before modification of the bridge was equal to 0,33%.

Conclusions

The automatic bridge described in the paper proved to be very convenient for the calibration of inductance standard in laboratories having the best calibration and measurement capability (CMC). Older types of the unbalance transformer bridge (KWL3 and KWL4) cooperated with digitally controlled switches are still successfully used at the National Metrology Institutes in Germany and Poland (PTB and GUM) for the calibration of 10 mH inductance standards at frequencies 1 kHz and 1592 Hz. It is expected that in the nearest future the KWL3 and KWL4 bridges will be replaced by the KWL5 which enables 1:1 comparison of inductors from 100 μH to 10 H in the frequency range from 100 Hz to 10 kHz with uncertainty smaller than 10 ppm.

First investigations of the KWL5 bridge done in 2005 help the constructors to improve the designed instrument. Positive results of the coherence test performed in 2007 allow to draw a conclusions about high accuracy of the bridge and its usefulness at NMIs for high-precision inductance measurements in the wide impedance and frequency ranges. Level of coherence for L differences measurements is less than 5 nH (5ppm) for 1 mH standards and less than 10 nH (1 ppm) for 10 mH standards.

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REFERENCES

[1] T. Skubis, A. Met, M. Kampik, *A Bridge for Maintenance of Inductance Standard*. IEEE Trans. on Instr. and Meas. No 6 (1999), vol. 48, 1161-1165.
[2] T. Skubis, A. Met., K. Musiol, *Coherence of Comparison Results for 10 mH Inductance Standards*. Instrumentation and Measurements Technology Conference IMTC'07, Warsaw, Poland, (2007), 1-3.
[3] K. Musiol, *A Digitally controlled switch for maintenance of inductance standards.* 2006 Conference on Precision Electromagnetic Measurements, Conference Digest CPEM, Torino (2006), 556-557.
[4] A. Carullo, M. Parvis, A. Vallan, L. Callegaro, *Automatic Compensation System for Impedance Measurement*. IEEE Trans. on Instr. and Meas. No 4 (2003), vol. 52, 1239-1242.
[5] L. Callegaro, V. D'Elia, J. Bohacek: Four-*Terminal-Pair Inductance Comparison Between INRIM and CTU*. IEEE Trans. on Instr. and Meas. No 1 (2009), vol. 58,

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