Проведено порівняльний аналіз отриманих у міжнародних звіреннях національних еталонів одиниць індуктивності результатів з метою оцінювання збіжності. Встановлені ступені еквівалентності еталонів учасників звірень та розширені невизначеності для номіналів мір 10 мГн і 100 мГн на частоті 1 кГц. Запропонована методика оцінювання невизначеності вимірювань у діапазоні значень індуктивності від 10 мкГн до 100 Гн

Ключові слова: звірення еталонів, метрологічна простежуваність, індуктивність, національний метрологічний інститут

Проведен сравнительный анализ полученных в международных сличениях национальных эталонов единиц индуктивности результатов с целью оценивания сходимости. Установлены степени эквивалентности эталонов участников сличений и расширенные неопределенности для номиналов мер 10 мГн и 100 мГн на частоте 1 кГц. Предложена методика оценки неопределенности измерений в диапазоне значений индуктивности от 1 мкГн до 100 Гн

Ключевые слова: сличения эталонов, метрологическая прослеживаемость, индуктивность, национальный метрологический институт

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A SUPPORT OF METROLOGICAL TRACEABILITY OF INDUCTANCE MEASUREMENTS IN UKRAINE

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1. Introduction

The growth of globalization of the world economy leads to the establishment of new trade requirements and economic preconditions that must be addressed by national metrological infrastructures. The main objective of the activity of metrological infrastructures at the national level is to achieve an acceptable level of satisfaction of the requirements of industry and science. Modern metrology is characterized by a high degree of international and regional coordination and close cooperation of all countries on a global scale, especially with regard to ensuring the equivalence of national standards from different countries.

Confirmation of equivalence of national standards with the standards of other countries is carried out under the procedures set at an international level within the framework of multilateral "Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes of CIPM" (hereinafter – the CIPM MRA) [1]. International comparisons of standards are conducted under the aegis of the Consultative Committees (CC) of the International Committee of Weights and Measures (CIPM) [2] or by regional metrology organizations (RMO) [3].

The metrological traceability is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty, in accordance with the International vocabulary of metrology (VIM) [4]. The practical application of the concept of metrological traceability allows comparing the accuracy of measurement according to the standardized procedure of estimation of measurement uncertainty [5].

The measurement uncertainty is determined as an inalienable parameter that characterizes dispersion of quantitative values that can be ascribed to the measurand on the basis of the information used, in accordance with the VIM. The basis for the evaluation of measurement uncertainty at an international level is the Guide to the expression of uncertainty in measurement (GUM) [6]. GUM is the basis for setting requirements of regional organizations for the evaluation of measurement uncertainty.

Calibration and Measurement Capabilities (CMC) are the greatest level of calibrations and measurements that are guaranteed by national metrology institutes (NMIs) to the consumers of metrology services [7]. CMC contain a value of the expanded uncertainty of the results of measurements conducted by NMIs at a confidence level of 0.95 and characterize the quality of metrological services provided to the consumers on a permanent basis [8].

For providing the metrological traceability of measurements of the inductance in Ukraine, at the international level, it was necessary to carry out the corresponding comparison of standards within the framework of RMO – Euro-Asian cooperation of national metrological institutions (COOMET), of which Ukraine is a member.

2. Literature review and problem statement

In [9], the analysis of the general international guides and standards that are used for the evaluation of elements of metrological traceability is conducted. The procedures used for the CIPM key comparison (KC) data evaluation are worked out in order to provide a connection with CIPM KC data [2].

The procedures used to evaluate the data of comparisons of standards in the framework of the RMO should be in accordance with the procedures established for the CIPM KC, in particular for the RMO KC [10], as well as for supplementary comparisons of RMO [11].

In [12], a general approach for evaluation of KC results is presented, in [13] – clarification of a general approach to the determination of the largest successive subset, in [14] – an example of the model of selection in the average of inconsistent data. However, in many practical cases of evaluation of comparison results, it is quite difficult and sometimes impossible to apply the specified approaches in practice. Thus, there is an urgent need for a detailed analysis of the approaches to assessing the comparison results set out in the final reports on comparison of standards of certain units of measurement.

In 1989–1999, international KC of national standards of the units of inductance with the nominal value of 10 mH CCEM-K3 within the framework of CC for electricity and magnetism (CCEM) of CIPM were conducted [15]. In 2002–2014, the specified comparisons became the basis for similar comparisons within the framework of different RMO. Within the framework of RMO of European countries, comparisons for the inductance of 10 mH in 2006 [16] and 100 mH on a frequency of 1 kHz in 2002–2003 [17] and 2006–2008 [18], RMO of American countries – for the inductance of 10 mH on a frequency of 1 kHz [19] in 2013–2014 took place. Within the framework of COOMET, the Ukrainian National Metrological Institute (NMI) participated in comparison for the inductance of 10 mH and 100 mH on a frequency of 1 kHz [20] in 2013–2014.

The evaluation of the state of providing the metrological traceability of measurements of inductance needs:

– scientific-reasonable selection of a methodology of analysis of the results of comparisons of national standards of inductance units of 10 mH and 100 mH and evaluation of equivalence of the existing national standard for the indicated inductances on a frequency of 1 kHz, having regard to the large variety of similar methodologies;

– development of a methodology of evaluation of measurement uncertainty of inductance in the range of inductance values from 10 μH to 100 H.

3. The aim and objectives of the study

The conducted studies aimed to estimate all basic components of the state of providing the metrological traceability of measurements of inductance in Ukraine.

For the achievement of the aim, such objectives were set:

– to carry out the comparative analysis of the results of COOMET international comparisons of national standards of the units of inductance with the aim of convergence evaluation;

– to determine the degrees of equivalence of standards of the comparison participants and expanded measurement uncertainties;

– to develop a methodology and conduct the evaluation of measurement uncertainties of inductance in a wide range of inductance values for the evaluation of existing CMC of Ukraine.

4. Materials and research methods within the framework of international comparisons of national standards of the unit of inductance

International supplementary comparison of national standards of the units of inductance of 10 mH and 100 mH on a frequency of 1 kHz for 2- and 3-terminals of measures were conducted within the framework of COOMET project 584/UA/12 (COOMET.EM-S14) with the participation of four NMIs during 2013-2014 [20]. Those NMI represent two RMO: COOMET and EURAMET. NMI participants of this comparison are: State Enterprise (SE) "Ukrmetrteststandard" (UMTS, Ukraine – pilot laboratory); GUM – Central Office of Measurement (Poland); KazInMetr – Kazakh Institute of Metrology (Kazakhstan); BelGIM – Belarusian State Institute of Metrology (Belarus).

In the comparison from Ukraine, the State primary standard of Ukraine of inductance units and dissipation factor (DETU 08-09-09) was presented, which is stored in the SE "Ukrmetrteststandard" (Kyiv, Ukraine). For carrying out the comparison, the transfer standard (TS) (thermostated measures) P5109 with the nominal value of 10 mH and P5113 with the nominal value of 100 mH was chosen [20].

Measurement of NMI participants was carried out under the following conditions:

– temperature: 23±1 °C;

– relative humidity: between 30 % and 70 %;

– measuring frequency: 1 kHz;

– full power (active and reactive) for the object of measurement shall not exceed 10 mW.

SE "Ukrmetrteststandard" as a pilot laboratory systematically carried out measurements for determination of time drift of TS for the nominal values of inductance measures of 10 mH and 100 mH on a frequency of 1 kHz for 2- and 3-terminals [20]. Having regard to the measurement results obtained by the pilot laboratory, it can be established that the drift was insignificant and did not have a substantial influence on the TS research results obtained by the NMIs participants. Taking into account the results of the measurements obtained by the pilot laboratory, it can be stated that the indicated drift was insignificant and did not have a significant impact on the results of researches of the TS obtained by the NMI participants.

Metrological traceability of the national standard of every NMI participant to SI units was given to the pilot laboratory [20]. For supplementary COOMET.EM-S14 comparison, the traceability of the national standards for the NMI participants was as follows:

– GUM – to the primary standard of capacitance unit of the International Bureau of Measures and Weights (BIPM);

– UMTS – to the primary standard of capacitance unit of the NIST (USA);

– KazInMetr and BelGIM – to the primary standard of inductance unit of the VNIIM (Russia).

Calculations of measurement uncertainty were carried out by each NMI participant in accordance with the ISO/IEC Guide 98-3 [6]. The NMI participants developed their own measurement uncertainty budgets for the nominal values of inductance measures of 10 mH and 100 mH.

The total standard uncertainty of measurements was included in the report on the research of the TS of the NMI participant, together with the measured inductance value.

The components of uncertainty in the uncertainty budget for the NMI participants were proposed to include at least the following:

– the experimental standard uncertainty of N independent measurements (type A);

– the uncertainty of the primary standard or other standard used in the research of the TS;

– the uncertainty of various values of inductance required for NMI.

The NMI participants could also include additional specific NMI-related components of measurement uncertainty.

5. Comparison of the results of international comparisons of standards

Deviations of the obtained values of inductance δL_i for the NMI participants of COOMET.EM-S14 comparison from the nominal values of 10 mH and 100 mH on a frequency of 1 kHz with the expanded uncertainties U_i are presented in Table 1. The indicated uncertainties have a coverage ratio of k=2 with a confidence interval of approximately 95 % [20].

Table 1

Deviations from the nominal value for the NMIs participants of COOMET.EM-S14 comparison with expanded uncertainties, mH/H

NMI participant	10 mH		100 mH		10 mH		100 mH	
	2-terminal				3-terminal			
	δL_i	U_i	δL_i	U_i	δL_i	U_i	δL_i	U_i
GUM	0.363	0.030	0.852	0.200	0.344	0.030	0.654	0.200
UMTS	0.386	0.020	0.865	0.148	0.367	0.020	0.667	0.148
KazInMetr	0.360	0.039	0.844	0.290	0.325	0.039	0.666	0.290
BelGIM	0.315	0.101	0.848	1.011	0.332	0.101	0.648	1.011

The reference value of comparisons x_{ref} is obtained as an average of all values of NMI participants of COOMET.EM-S14 comparison by the expression

$$x_{ref} = \sum_{i=1}^{N} \frac{x_i}{u^2(x_i)} \bigg/ \sum_{i=1}^{N} \frac{1}{u^2(x_i)}, \tag{1}$$

with the corresponding standard uncertainty

$$u^2(x_{ref}) = 1 \bigg/ \sum_{i=1}^{N} \frac{1}{u^2(x_i)}, \tag{2}$$

where x_i is the i-th result of the NMI participant of COOMET.EM-S14 comparison; $u(x_i)$ is the standard uncertainty of the result of the i-th NMI participant of COOMET.EM-S14 comparison; N is the number of COOMET.EM-S14 comparison (N=4) participants.

The calculated values of reference values of COOMET.EM-S14 comparison with the expanded uncertainties are given in Table 2.

Table 2

Reference values of COOMET.EM-S14 comparison with expanded uncertainties, mH/H

Inductance 10 mH				Inductance 100 mH			
2-terminal		3-terminal		2-terminal		3-terminal	
x_{ref}	U_{ref}	x_{ref}	U_{ref}	x_{ref}	U_{ref}	x_{ref}	U_{ref}
0.375	0.015	0.354	0.015	0.858	0.110	0.663	0.110

The degree of equivalence of the standard of the i-th NMI and expanded uncertainties in the sense of reference values of comparisons were determined by the expressions

$$D_i = x_i - x_{ref}, \tag{3}$$

$$u^2(D_i) = u^2(x_i) - u^2(x_{ref}). \tag{4}$$

The declared uncertainties of NMIs participants must satisfy the following inequality

$$|D_i| < 2u(D_i). \tag{5}$$

The degrees of equivalence (DoE) of standards of NMI participants in COOMET.EM-S14 comparison with expanded uncertainties (k=2) for 10 mH and 100 mH for 2- and 3-terminals in the sense of the reference value of comparison are presented in Table 3 and Fig. 1–4 [20].

Table 3

Degrees of equivalence of standards of NMI participants of COOMET.EM-S14 comparison with expanded uncertainties, mH/H

NMI participant	10 mH		100 mH		10 mH		100 mH	
	2-terminal				3-terminal			
	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$
GUM	–0.012	0.026	–0.006	0.168	–0.010	0.026	–0.009	0.168
UMTS	0.012	0.013	0.007	0.100	0.013	0.013	0.004	0.100
KazInMetr	–0.015	0.036	–0.014	0.269	–0.029	0.036	0.003	0.269
BelGIM	–0.060	0.100	–0.010	1.005	–0.022	0.100	–0.015	1.005

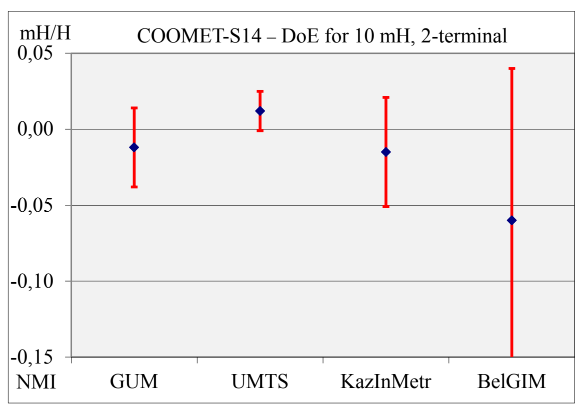

Fig. 1. Degrees of equivalence for NMI participants COOMET.EM-S14 comparison for 10 mH (2-terminal)

All NMI participants of the mentioned comparison of standards received satisfactory results for 2- and 3-terminals.

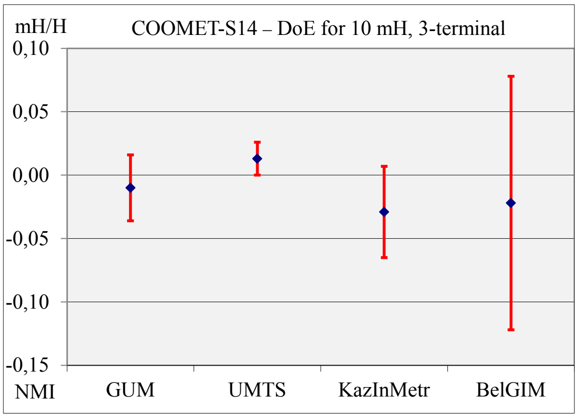

Fig. 2. Degrees of equivalence for NMI participants COOMET. EM-S14 comparison for 10 mH (3-terminal)

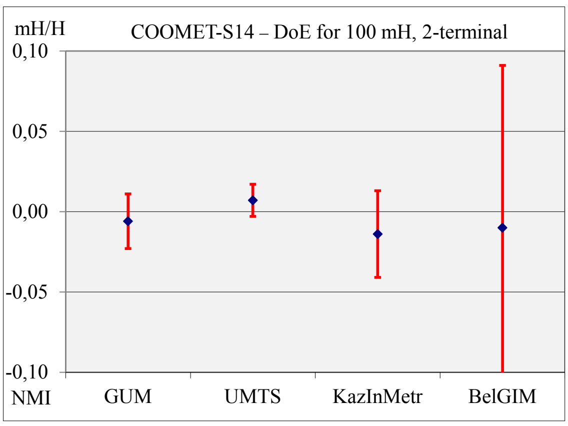

Fig. 3. Degrees of equivalence for NMI participants COOMET. EM-S14 comparison for 100 mH (2-terminal)

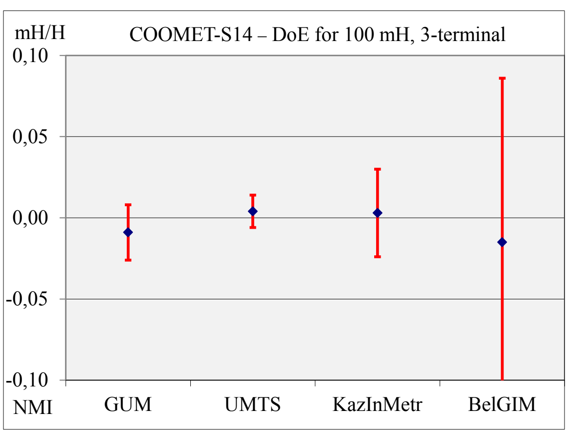

Fig. 4. Degrees of equivalence for NMI participants COOMET. EM-S14 comparison for 100 mH (3-terminal)

6. Results of verifying the consistency of the comparisons' results

The calculated values of the χ^2 criterion (Table 4) for the results of comparisons of standards of NMI participants taking into account the measurement uncertainties ($\{x_i, u(x_i)\}$, i=1, ...N) were calculated by the expression [11]

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - x_{ref})^2}{u^2(x_i)}. \tag{6}$$

The value for the criterion χ^2 for COOMET.EM-S14 comparison does not exceed the critical values with the coverage level of 0.95 by the inequality

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - x_{ref})^2}{u^2(x_i)} \prec \chi^2_{0.95}(N-1), \tag{7}$$

i. e., the obtained values of NMI participants can be considered consistent, which is the objective confirmation of the measurement uncertainties declared by NMI participants.

The maximum of the E_N criterion for NMI participants was calculated by the expression [11]

$$\max_i E_N = \frac{\left|x_i - x_{ref}\right|}{2\sqrt{u^2(x_i) - u^2(x_{ref})}}. \tag{8}$$

The verification was carried out consistently for each NMI participant. The maximum of the E_N criterion for the declared uncertainties and the obtained degrees of equivalence for all NMI participants in the COOMET.EM-S14 for 10 mH and 100 mH satisfies equations (7) and (8) and is shown in Table 4.

Table 4

The calculated values for the criteria χ^2 and E_N for the nominal values of inductance of 10 mH and 100 mH

NMI participant	Inductance, mH	$\chi^2 \prec \chi^2_{0.95}(n-1) = 7.81$		E_N	
		2-terminal	3-terminal	2-terminal	3-terminal
GUM	10	3.99	4.49	0.46	0.39
UMTS				0.89	0.99
KazInMetr				0.42	0.80
BelGIM				0.60	0.22
GUM	100	2.22	1.23	0.35	0.52
UMTS				0.71	0.43
KazInMetr				0.52	0.12
BelGIM				0.10	0.15

All NMI participants of the specified comparison of standards have a satisfactory agreement on the obtained results.

7. Evaluation of uncertainty in the calibration of inductance measures

To calibrate high-precision inductance measures, traceability from a calibrated high-precision measure of capacity of 100 pF or 10 pF with the appropriate uncertainty should be ensured.

The State primary standard of the units of electrical capacitance and dissipation factor DETU 08-06-01 includes the group of four precision capacitance measures Andeen-Hagerling (USA) AH11A (4 measures with the nominal value of 10 pF and 4 measures with the nominal value of 100 pF). Due to the calibration of the specified measures at a frequency of 1 kHz conducted at NIST (USA), PTB (Germany) and NPL (Great Britain), as well as own constant research, the value of the electrical capacitance of all capacitance measures AH11A is known with the expanded uncertainty $U(C_{AH})$=7.4·10^{-6} pF with the probability P=0.95 at the coverage factor k=2 [21].

The transmission of the unit size of inductance over the value range is carried out with the use of the universal automated precision comparator included in the DETU 08-09-09 standard. The comparator has the following transmission ratio values: 1:1; 1:10 or 10:1. Using these transmission ratio values only, it is possible to realize the transmission of the unit size of inductance from the capacitance measure by consecutive calibrations in the wide range of values towards both high and low impedance [22].

An example of transmission of the unit size of inductance over the value range from the capacitance measure in the calibration of inductance measures with the nominal values from 1 μH to 100 H is represented in Fig. 5.

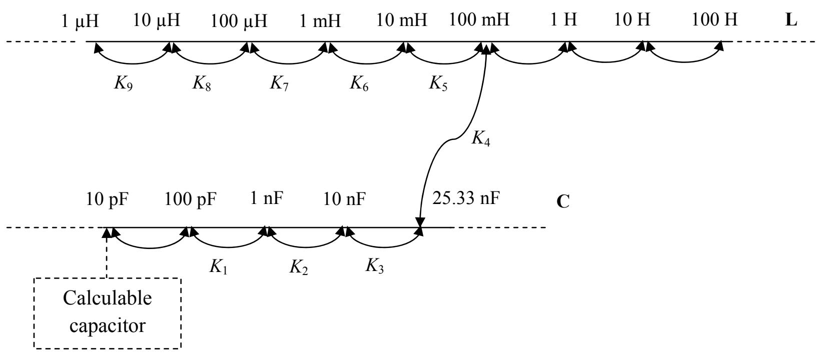

Fig. 5. The transmission of the unit size of inductance over the value range with the basis on the calculable capacitor

The model (equation) of measurements follows from the measurement scheme:

$$L_X = \frac{K_5 K_6 K_7 K_8 K_9}{\omega^2 K_1 K_2 K_3 K_4 C_{100\,pF}}, \tag{9}$$

where ω is the operating frequency of the test signal 6279.897 rad/s (1 kHz) on which measurements are made;

$$C_{100\mathrm{pF}} = C_S + \Delta C_{TS} + \Delta C_{fS} + \Delta C_{\gamma S}, \tag{10}$$

$C_{100\mathrm{pF}}$ is the actual value of the Andeen-Hagerling AN11A capacity measure with the nominal value of 100 pF, taking into account the drift of the main parameter, as well as other influential factors;

C_S is the value of the Andeen-Hagerling AN11A capacity indicated in the calibration certificate;

ΔC_{TS} is correction for the temperature dependence of the capacitance measure AH11A;

ΔC_{fS} is correction for the frequency dependence of the capacitance measure AH11A;

$\Delta C_{\gamma S}$ is correction for the drift of the measure AH11A since the last calibration;

K_1, K_2, K_3 are the transmission coefficients of the comparator in the calibration of the capacitance measure 1 nF, 10 nF and 25.33 nF with the basis on the capacitance measure AH11A with the nominal value of 100 pF, for the box of temperature-stabilized capacitance measures CA 5200RC 1 nF and 10 nF, accordingly:

$$K_1 = \frac{C_{1\mathrm{nF}}}{C_{100\mathrm{pF}}},\quad K_2 = \frac{C_{10\mathrm{nF}}}{C_{1\mathrm{nF}}},\quad K_3 = \frac{C_{25.33\mathrm{nF}}}{C_{10\mathrm{nF}}}; \tag{11}$$

K_4 is the transmission coefficient of the comparator in the calibration of the inductance measure with the basis on the intermediate capacitance measure 25.33 pF on the frequency ω;

K_5, K_6, K_7, K_8, K_9 are the transmission coefficients of the comparator in the calibration of the inductance measure 10 mH, 1 mH, 100 μH, 10 μH and 1 μH with the basis on the intermediate inductance measure 100 mH, 10 mH, 1 mH, 100 μH and 10 μH, accordingly:

$$K_5 = \frac{L_{10\mathrm{mH}}}{L_{100\mathrm{mH}}},\quad K_6 = \frac{L_{1\mathrm{mH}}}{L_{10\mathrm{mH}}},\quad K_7 = \frac{L_{100\mu\mathrm{H}}}{L_{1\mathrm{mH}}},$$

$$K_8 = \frac{L_{10\mu\mathrm{H}}}{L_{100\mu\mathrm{H}}},\quad K_9 = \frac{L_{1\mu\mathrm{H}}}{L_{10\mu\mathrm{H}}}. \tag{12}$$

The example of the uncertainty budget of measurements of the capacitance value in the calibration of the capacitance measure AH11A C_X is presented in Table 5.

The example of the uncertainty budget of measurements of the inductance value in the calibration of the inductance measure L_X with the basis on the capacitance measure AH11A $C_{100\mathrm{pF}}$ is presented in Table 6.

Calculation of the relative total standard uncertainty $w(L_X)$ and relative expanded uncertainty $W(L_X)$ in the transmission of the unit size of the physical quantity from the capacitance measure AH11A with the nominal value of 100 pF to the calibrated inductance measure L_X with the nominal value of 1 μH is carried out in a relative form by the formulas:

$$w(L_X) = \sqrt{w^2\left(C_{100\,pF}\right) + \sum_{i=1}^{N} p_i^2 w_i^2\left(x_i\right)}, \tag{13}$$

$$W(L_X) = kw(L\ ). \tag{14}$$

Table 5

The measurement uncertainty budget in the calibration of the capacitance measure AH11A C_X

Quantity X_i	Value x_i	Standard uncertainty $u(x_i)$, pF	Distribution law	Type of evaluation	Sensitivity coefficient c_i	Contribution to uncertainty $c_i \cdot u(x_i)$, pF
C_S	100,000020 pF	$3.70\cdot10^{-5}$	normal	A	1	$3.70\cdot10^{-5}$
ΔC_{TS}	0 pF	$7.10\cdot10^{-7}$	normal	B	1	$7.10\cdot10^{-7}$
ΔC_{fS}	0 pF	$4.10\cdot10^{-7}$	normal	B	1	$4.10\cdot10^{-7}$
$\Delta C_{\gamma S}$	$-1.10\cdot10^{-6}$ pF	$5.80\cdot10^{-7}$	normal	B	1	$5.80\cdot10^{-7}$
C_X	100.0000189 pF	–				
Total standard uncertainty					$u(C_X)$	$3.70\cdot10^{-5}$
Effective number of degrees of freedom					ν_{eff}	>200, k=2
Relative expanded uncertainty (P≈0.95)					$U(C_X)$	$7.40\cdot10^{-5}$

In the sense of the standard uncertainty of the coefficients K_1, K_2, ..., K_9, the following is taken account: the deviation due to the error of the quantization of the comparator; correction for the sensitivity of the comparator and the error of comparison. The values of the coefficients K_1, K_2, ..., K_9 are given in the passport of the comparator, but can be specified for each point of the measurement range by comparing pre-calibrated high-precision measures.

Table 6

The measurement uncertainty budget in the calibration of the inductance measure L_X with the basis on the capacitance measure AH11A C_{100pF}

Quantity X_i	Value x_i	Relative standard uncertainty $w(x_i)$	Distribution law	Type of evaluation	Sensitivity coefficient p_i	Contribution to uncertainty $p_i \cdot w(x_i)$
C_{100pF}	100.000019 pF	$3.83 \cdot 10^{-7}$	normal	B	–1	$-3.83 \cdot 10^{-7}$
ω	6283.185 rad/s	$1.00 \cdot 10^{-7}$	normal	B	–2	$-2.00 \cdot 10^{-7}$
K_1	10.000245	$1.20 \cdot 10^{-6}$	normal	A	–1	$-1.20 \cdot 10^{-6}$
K_2	10.000239	$1.20 \cdot 10^{-6}$	normal	A	–1	$-1.20 \cdot 10^{-6}$
K_3	2.532112	$1.50 \cdot 10^{-6}$	normal	A	–1	$-1.50 \cdot 10^{-6}$
K_4	10.100035	$7.00 \cdot 10^{-6}$	normal	A	–1	$-7.00 \cdot 10^{-6}$
K_5	0.099970	$1.50 \cdot 10^{-6}$	normal	A	1	$1.50 \cdot 10^{-6}$
K_6	0.100041	$1.50 \cdot 10^{-6}$	normal	A	1	$1.50 \cdot 10^{-6}$
K_7	0.099982	$2.00 \cdot 10^{-6}$	normal	A	1	$2.00 \cdot 10^{-6}$
K_8	0.099999	$3.00 \cdot 10^{-6}$	normal	A	1	$3.00 \cdot 10^{-6}$
K_9	0.100001	$5.00 \cdot 10^{-6}$	normal	A	1	$5.00 \cdot 10^{-6}$
L_X	0.990337 μH	–				
Relative total standard uncertainty					$w(L_X)$	$9.84 \cdot 10^{-6}$
Effective number of degrees of freedom					ν_{eff}	>200, k=2
Relative expanded uncertainty ($P \approx 0.95$)					$W(L_X)$	$3.46 \cdot 10^{-5}$

It should be noted that in the relative total standard measurement uncertainty of the calibration result, it is also necessary to take into account the frequency dependence of the transmission factor of the comparator. Frequency instability has a significant effect on the result of measurements when calibrating both the capacity measurements and the measures of inductance. However, during the measurements, the frequency drift is negligible and the measurement uncertainty is about the value of $1 \cdot 10^{-10}$. Thus, the components of uncertainty introduced by the frequency dependence can be neglected.

The measured value of inductance of the measure with the nominal value of 1 μH at the measurement temperature of (22÷24) °C and relative humidity of (30÷45) % at the frequency of the examined signal of 1 kHz made up 0.990337 μH $\pm 3.46 \cdot 10^{-5}$.

CMC of NMIs of countries are published as pdf files in the Annex C of the BIPM Key Comparison Database (KCDB) in the form of tables [8]. The above-mentioned values of measurement uncertainties correspond to the data published in the KCDB for Ukraine in the range of inductance values from 10 μH to 10 H.

8. Discussion of the results of evaluating the state of the metrological traceability of inductance measurements

The comparative analysis of the results of the RMO international supplementary comparison of national standards of the units of inductance showed the convergence of the results for 10 mH and 100 mH on a frequency of 1 kHz. This allowed determining the degrees of equivalence of standards of NMI participants and expanded uncertainties for the specified nominal values of inductance measures. Metrological traceability to the units of the International system of units SI of the national standard of Ukraine to the primary standard of the unit of capacitance of the NIST (USA) is determined.

Verification of consistency of the results of comparisons of NMI participants taking into account the measurement uncertainties on the criterion χ^2 showed that the results can be considered consistent. This is the objective confirmation of the measurement uncertainties declared by the participants.

The results of the calculations of the values of measurement uncertainties according to the proposed methodology of evaluation of measurement uncertainty in a wide range of inductance values (from 10 μH to 10 H) showed that the measurement uncertainties correspond to the data published in the international key comparison database for Ukraine on CMC for inductance units in the range of inductance values from 10 μH to 10 H on a frequency of 1 kHz.

9. Conclusions

1. The comparative analysis of the results of the international supplementary comparison of the national standards of the units of inductance for 2- and 3-terminals of inductance measures is conducted with the aim of evaluation of convergence. For the comparisons, the reference values with the expanded uncertainties are calculated and the degrees of equivalence of standards of participants and expanded uncertainties for the nominal values of measures of 10 mH and 100 mH on a frequency of 1 kHz are determined. Metrological traceability of the national standard of every participant of comparisons to the units of the International system of units SI is determined.

2. For verification of consistency of the results of comparisons, the values of the χ^2 criterion for the results of comparison of standards of participants taking into account the measurement uncertainties are calculated. The obtained values of the criterion of consistency for the participants can be considered consistent, which is the objective confirmation of the measurement uncertainties declared by the participants.

3. The methodology of evaluation of measurement uncertainty in a wide range of inductance values is proposed. The results of the calculations of the values of measurement uncertainties revealed that the results correspond to the data published in the international key comparison database for Ukraine in the range of inductance values from 10 μH to 10 H on a frequency of 1 kHz.

References

1. Text of the CIPM MRA [Electronic resource]. – Available at: http://www.bipm.org/en/cipm-mra/cipm-mra-text/
2. Measurement comparisons in the context of the CIPM MRA. CIPM MRA-D-05:2013 [Electronic resource]. – Available at: http://www.bipm.org/utils/common/documents/CIPM-MRA/CIPM-MRA-D-05.pdf

3. The BIPM key comparison database (KCDB) [Electronic resource]. – Available at: http://kcdb.bipm.org/
4. JCGM 200:2012. International vocabulary of metrology. – Basic and general concepts and associated terms (VIM 3-rd edition) [Electronic resource]. – Available at: http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf
5. Velichko, O. N. Traceability of measurement results at different levels of metrological work [Text] / O. N. Velichko // Measurement Techniques. – 2009. – Vol. 52, Issue 11. – P. 1242–1248. doi: 10.1007/s11018-010-9428-7
6. Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement (GUM). JCGM 100:2008 [Electronic resource]. – Available at: http://www.bipm.org/en/publications/guides/gum.html/
7. Calibration and Measurement Capabilities in the context of the CIPM MRA. CIPM MRA-D-04:2013 [Electronic resource]. – Available at: http://www.bipm.org/en/cipm-mra/cipm-mra-documents/
8. Velichko, O. N. Calibration and measurement capabilities of metrological institutes: features of preparation, examination, and publication [Text] / O. N. Velichko // Measurement Techniques. – 2010. – Vol. 53, Issue 6. – P. 721–726. doi: 10.1007/s11018-010-9567-x
9. Velychko, O. The implementation of general international guides and standards on regional level in the field of metrology [Text] / O. Velychko, T. Gordiyenko // Journal of Physics: Conference Series. – 2010. – Vol. 238. – P. 012044. doi: 10.1088/1742-6596/238/1/012044
10. COOMET R/GM/14:2016 [Electronic resource]. – Available at: http://www.coomet.org/DB/isapi/cmt_docs/2016/5/2BMD1O.pdf
11. COOMET R/GM/19:2016 [Electronic resource]. – Available at: http://www.coomet.org/DB/isapi/cmt_docs/2016/5/21XQGO.pdf
12. Cox, M. G. The evaluation of key comparison data [Text] / M. G. Cox // Metrologia. – 2002. – Vol. 39, Issue 6. – P. 589–595. doi: 10.1088/0026-1394/39/6/10
13. Cox, M. G. The evaluation of key comparison data: determining the largest consistent subset [Text] / M. G. Cox // Metrologia. – 2007. – Vol. 44, Issue 3. – P. 187–200. doi: 10.1088/0026-1394/44/3/005
14. Mana, G. Model selection in the average of inconsistent data: an analysis of the measured Planck-constant values [Text] / G. Mana, E. Massa, M. Predescu // Metrologia. – 2012. – Vol. 49, Issue 4. – P. 492–500. doi: 10.1088/0026-1394/49/4/492
15. Eckardt, H. International Comparison of 10 mH Inductance Standards at 1 kHz. CCEM-K3. Final Report. CCEM WGKC/2001-15 [Text] / H. Eckardt. – PTB, 2001. – 35 p.
16. Kölling, A. Final report on EUROMET comparison EUROMET.EM-K3: a 10 mH inductance standard at 1 kHz [Text] / A. Kölling // Metrologia. – Vol. 48, Issue 1A. – P. 01008–01008. doi: 10.1088/0026-1394/48/1a/01008
17. Callegaro, L. EUROMET.EM-S20: Intercomparison of a 100 mH inductance standard (Euromet Project 607) [Text] / L. Callegaro // Metrologia. – 2007. – Vol. 44, Issue 1A. – P. 01002–01002. doi: 10.1088/0026-1394/44/1a/01002
18. Dierikx, E. Final report on the supplementary comparison EURAMET.EM-S26: inductance measurements of 100 mH at 1 kHz (EURAMET project 816) [Text] / E. Dierikx, A. Nestor, J. Melcher, A. K lling, L. Callegaro // Metrologia. – 2011. – Vol. 49, Issue 1A. – P. 01002–01002. doi: 10.1088/0026-1394/49/1a/01002
19. Moreno, J. A. SIM.EM-K3 Key comparison of 10 mH inductance standards at 1 kHz [Text] / J. A. Moreno, M. Côté, A. Koffman, B. I. Castro, R. de B. e Vasconcellos, G. Kyriazis et. al. // Metrologia. – 2016. – Vol. 53, Issue 1A. – P. 01002–01002. doi: 10.1088/0026-1394/53/1a/01002
20. Velychko, O. Final report on COOMET supplementary comparison of inductance at 10 mH and 100 mH at 1 kHz (COOMET.EM-S14) [Text] / O. Velychko, S. Shevkun // Metrologia. – 2016. – Vol. 53, Issue 1A. – P. 01009–01009. doi: 10.1088/0026-1394/53/1a/01009
21. Velychko, O. Support of metrological traceability of capacitance measurements in Ukraine [Text] / O. Velychko, S. Shevkun // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 3, Issue 9 (87). – P. 4–10. doi: 10.15587/1729-4061.2017.101897
22. Shevkun, S. Evaluation of uncertainty of inductance measures on state primary standard of the unit of inductance [Text] / S. Shevkun, M. Surdu, O. Velichko // 18th TC4 IMEKO Symposium and IX International Congress on Electrical Metrology «Metrologia-2011». – At Natal, 2011. – P. 168–171.