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# Establishment of a National Primary Inductance Standard Unit

**Han Jun Kim† , Rae Duk Lee*, Yu. P. Semenov** and Sang Ok Han*****

**Abstract** - A portable primary inductance standard set that includes a Maxwell-Wien bridge and a 10 mH standard inductor installed in a thermostat has been developed at KRISS. Two auxiliary resistance-capacitance networks (analogous to a "Wagner ground") provide excellent stability of the bridge balance and impose less strict requirements on the components of these networks. Removable capacitance and ac-dc resistance standards used in the bridge arms made it possible to reproduce 10 mH and 100 mH inductance values in the frequency range of 500 Hz to 3 kHz. From investigations of this standard and preliminary comparison with VNIIM (D. I. Mendeleyev Institute for Metrology), the results have demonstrated that the bridge can be used as a part of the transportable inductance standard with a measurement uncertainty within (1-3) μH/H at frequencies of 1 kHz and 1.6 kHz. The application of the bridge as a constituent part of the transportable standard gives us an opportunity to eliminate the influence of the standard inductors.

**Keywords:** capacitors, inductance measurement, Maxwell-Wien bridge, resistors, standards

## 1. Introduction

Commercialized four terminal-pair (4T-P) RLC meters enable the measurement of impedance of resistors, capacitors, and inductors in the frequency range of 10 Hz to 2 MHz over a wide range of nominal values. According to its specifications, the most accurate measurement range of the 4T-P RLC meter has a basic relative uncertainty of $500\times10^{-6}$. However, these meters have a basic accuracy 4-5 times higher in the middle frequency range, i.e., an uncertainty of $(100\text{-}120)\times10^{-6}$, with a resolution and repeatability of $(0.1\text{-}1)\times10^{-6}$ and an uncertainty, due to the nonlinearity, of $(1\text{-}2)\times10^{-6}$. This means that, on the one hand, these meters can be used for the calibration of the most accurate impedance standards at calibration laboratories by the substitution method and furthermore, that they must be certified with traceability to the national impedance standard to an uncertainty of 0.01-0.001%. This task has been accomplished successfully for the capacitance standards i.e., the unit of capacitance has been established using primary standards to an uncertainty of (0.02-0.05) μF/F, and has been compared among various national metrological institutes (NMIs), BIPM (Bureau International des Poids et Mesures), CCEM (Consultative Committee for Electricity and Magnetism), and RMO (Regional Metrology Organization), and has covered a wide range of nominal values and frequencies up to 1 MHz.

However, the situation regarding inductance standards is quite different. In most NMIs, the unit of inductance (the Henry) is not maintained as a primary standard, but is realized in terms of capacitance and frequency and/or resistance, with an accuracy that is two orders lower than that of the ohm and the farad. International comparisons have been carried out only a few times, including the CCEM K-3 (1989-1997), and EUROMET (European Collaboration in Measurement Standards) comparisons (1982-1985) [1, 2]. This situation can be explained by two reasons. One is that it is not necessary to maintain the unit of Henry as a primary standard because of the instability of the standards, which was shown by comparing the results of the above assessments. For example, the drift in transportable standards was -18 to -37 (μH/H)/y during the EUROMET comparison. The other reason is that comer-cial inductance standards do not have a sufficiently precise electrical definition because they are used as two terminal components. However, the results of the CCEM K-3 comparison demonstrated that a standard inductor placed in a thermostat could be a reliable instrument for comparisons with accuracy in the order of μH/H. This can be achieved by a more careful definition of connectors and by the pilot laboratory employing sequential monitoring of the values obtained. Although the same type of standard inductor was used in the comparisons in 1982, the drift in the inductance standard in this comparison was 0.242 (μH/H)/m, which is one order of magnitude lower than that of the EUROMAT comparison mentioned above. Thus, we need to develop the necessary methods and instruments for accurate calibration

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of inductance standards, as well as for compare-son of inductance standards.

Our goal is to build an instrument that can reproduce the unit of inductance to the highest accuracy in terms of resistance and capacitance, and which would be both sufficiently reliable and compact for transportation. This transportable instrument including a standard inductor would exclude the main source of measurement uncertainty due to the instability in the standards during the inter-laboratory comparisons. Therefore, a compact inductance standard (CIS) consisting of a Maxwell-Wien bridge (MWB), a 10 mH standard inductor installed in a thermostat, a 10 nF standard capacitor, two standard ac resistors, and a substitution resistor, has been developed at KRISS.

## 2. Comparisons Using the CIS

When the CIS is circulated among the NMIs, it is possible to make a new concept of inductance comparison for the interlaboratory comparisons and key comparisons.

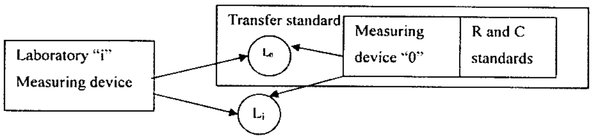

**Fig. 1** Procedure for intercomparison using a transportable inductance standard.

The stability of the standard resistor and the standard capacitor of the CIS is 10 to 50 times better than that of the standard inductor. This stability is thus sufficient to monitor the stability of the standard inductor. In key comparisons, the standard inductor, $L_i$, maintained at each participating laboratory, is calibrated using both the laboratory's own equipment and the CIS. After that, the standard inductor included in the CIS, $L_0$, is measured using the same procedure, which is shown in Fig. 1. This new comparison procedure will significantly reduce the circulation time because it is not necessary to return the transfer standard to the pilot laboratory periodically. The reliability of the comparison results is improved by analyzing the information received from each participating laboratory.

## 3. Bridge

### 3.1 Electric Circuits

Several types of circuit can be used to measure inductance in terms of resistance and capacitance. Among these circuits, the MWB circuit is different from the others because its balance equation does not depend on the frequency. The MWB can therefore be used for a wide range of nominal values and frequencies. However, the accuracy of the MWB is limited by the influence of ground admittances induced between the nodes and the ground of the MWB. The influence of these ground admittances can be eliminated using a complex system of screens [5], applying the substitution method, and using the "Wagner ground" or additional networks to achieve a source balance [4, 6]. The MWB circuit was chosen for our transportable standard (i.e., CIS). We will highlight some peculiarities of the MWB circuit and its construction, because the systematic errors experienced depend on the basic bridge circuit, and also on the details of its realization and the measurement process. The influence of ground admittances on the main bridge balance can be eliminated using two auxiliary series circuits: a "source balance" and a "detector balance" [4]. To exclude the effect of ground admittances in our four-arm bridge having a directly connected detector, it was sufficient to adjust only one of these auxiliary series circuits. For example, adjustment of the "source balance" circuit stabilized the bridge and led to a zero influence of the ground admittances. This was fully equivalent to applying a "Wagner ground".

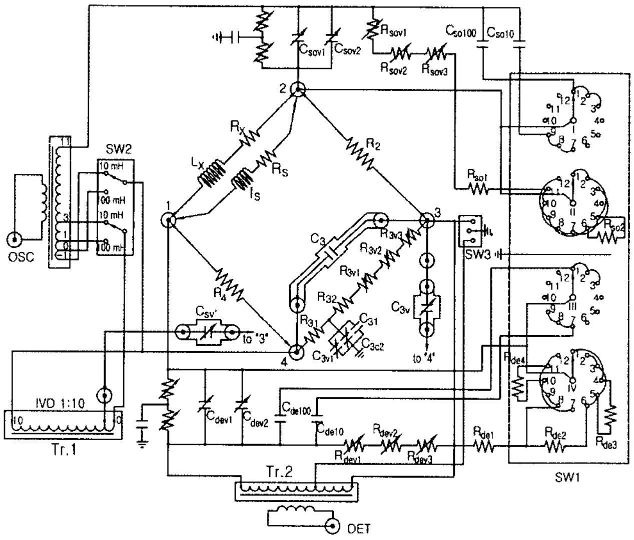

**Fig. 2** A circuit diagram of the MWB

The balance conditions between the bridge and an auxiliary circuit included the relatively unstable ground admittances and output impedances of the sources and impedances of conductors, and it was difficult to adjust these conditions and maintain them for a long period. Thus, it is quite reasonable to assume that a certain residual imbalance of the auxiliary circuit always exists. The redundant adjustment using the detector balance included in the balancing procedure contributes to an improved immunity of the main balance condition against the instability of the auxiliary circuit parameters. This enables the adjustment to be simple and allows the use of adjustable components that are not very accurate in the auxiliary circuits. It is especially important to fabricate a compact bridge. The use of the zero-substitution method and of a specially designed standard capacitor and resistor make it possible to eliminate the influence of the residual parameters of the resistor and capacitor on the balance condition. The zero-substitution method stipulates that the inductor to be measured is substituted by a substitution resistor that has the same nominal resistance as the intrinsic resistance of the standard inductor and the clarified minimum inductance [3]. The balance condition of the MWB using the substitution method is given in (1).

$$L_x = \frac{\Delta C_3 \cdot R_2 \cdot R_4 \cdot \lfloor 1 - \omega^2 \cdot l_s \cdot C_s + F(\tau, \delta) \rfloor + l_s + \left(R_x^2 - R_s^2\right) \cdot C_s - (l_1 - l_{1s})}{1 + \omega^2 \cdot \left[ l_s (C_s - C_{ss}) + \Delta C_3 \cdot R_2 \cdot R_4 \cdot C_s \right]} \tag{1}$$

where $\Delta C_3$ is the capacitance increment in arm 3, $R_2$ and $R_4$ are the resistances in arms 2 and 4, respectively, $l_s$ is the inductance of the substitution resistor, $C_s$ is the capacitance of the bridge terminals connecting the inductor, $C_{ss}$ is the capacitance of the bridge terminals connecting the substitution resistor, $F(\tau, \delta)$ is a function of the products of the residual parameters, $l_1$ is the inductance in arm 1 connected in series with inductor $L_x$, $l_{1s}$ is the inductance in arm 1 connected in series with the substitution resistor, $R_x$ is the resistance of the inductor to be measured, and $R_s$ is the resistance of the substitution resistor.

Firstly, the balance of the MWB is obtained by adjusting capacitor $C_3$ and conductance $G_3$ in arm 3. Secondly, the balance is re-established by adjusting $C_3$ and the resistance of the substitution resistor in arm 1. The resistance and shunt capacitance in arm 3 need to be constant during both balancing procedures, so that the influence of this capacitance on the bridge balance is completely excluded. In both balancing procedures, arm 1 of the MWB contains either the inductor to be measured (in the first balancing procedure), or the substitution resistor (in the second balancing procedure). This eliminates the uncertainty caused by the capacitance leakage from the connection point of the components, which arises from the in-series connection in arm 1 of the bridge, as is observed in most conventional bridges. Two networks were used to couple the main bridge with a source and a detector. Each of these contained a ratio transformer and an adjustable resistance-capacitance network with a T-shaped circuit that generated negative conductivity values to compensate for the output impedance of the corresponding ratio transformer. Arm 3 also included a T-shaped resistance-capacitance network to maintain the bridge balance during the measurement of the substitution resistor in the condition of the following inequality presented due to the residual parameters of the components

$$l_s \leq \frac{R_2 R_4}{R_3} (\tau_2 + \tau_4 - \tau_3) \tag{2}$$

Where $\tau_i$ is the time constant of resistor $R_i$. If this inequality exists, then the bridge cannot be balanced, even with a zero capacitance value in arm 3, as the increased capacitance $C_3$ leads to a further increase in the unbalance. To control the processes of “source balance”, “detector balance”, and “main balance”, the earth point of the bridge was connected to both node 3 and the tap of transformer Tr 2, or was switched off by SW3 because only one detector connected between nodes 1 and 3 was used constantly. The use of a 10:1 turns ratio transformer (Tr 1) provided the possibility of using variable capacitors with a capacitance of 10 or 100 pF to establish the main balance. For the same purpose, a special compact device that contained a four-decade inductive voltage divider and a 100 pF capacitor was developed. The bridge function switch (SW1) enabled a fixed offset for each balance network in turn to check the accuracy of the adjustment of the corresponding network. The offset value was chosen such that it was possible to check the adjustment of each auxiliary circuit and its influence on the main balance at any time without changing the detector sensitivity.

### 3.2 Parameters of the Bridge Components

By using British Post Office (BPO) MUSA connectors, the standard resistors $R_2$ and $R_4$ were connected directly to the bridge connectors without using any interface cables, so that the bridge nodes coincided spatially with the points of the 2T-P definition of these standards. Multiturn potentiometers and variable air capacitors were applied to adjust all the parameters except the capacitor for the main balance. The T-circuit in arm 3 generated a negative capacitance from -3 to -13 pF to compensate the initial capacitance of arm 3, and to balance the bridge. The resistance of arm 3 was adjustable between 100 kΩ and 140 kΩ, with a resolution of 0.05 Ω, matched with an inductance resolution of $1 \times 10^{-6}$. The negative value of the effective capacitance in the auxiliary balance circuits was adjusted within 0-100 pF to compensate for an alteration of the output impedance of the transformers when the frequency was changed. All parts of the MWB were screened effectively and placed in separate compartments of the case. The connections were achieved by means of coaxial cables, and both ratio transformers had double screens. The screening of the terminals is important for precise measurement of the inductor, because the effect of the capacitance of the terminals is not eliminated using the substitution method. The MWB was constructed in a potable case, and the dimensions (including the standard resistors, $R_2$ and $R_4$, and the standard capacitor, $C_3$) were 250(W)×220(D)×220(H) mm.

### 3.3 Capacitance and Resistance Standards

The 10 nF standard capacitor used was a highly stable hermetically sealed capacitor with a ceramic dielectric. Its characteristics have been described in the proceeding of CPEM 2002 [7]. Its temperature coefficient and loss angle at a frequency of 1 kHz were -0.5 (μF/F)/K and 87 μrad, respectively. The correction for the frequency variation in the frequency range of 300 Hz to 3 kHz was -99 μF/F. The two 1 kΩ and the 10 kΩ standard resistors used were manufactured using large-size metal-foil chip-resistors, whose long-term stability was better then 1 (μΩ/Ω)/y. The standard resistors had a double definition in their connectors, i.e., 2T-P definition for ac resistance measurements at the MWB, and four terminal definition for dc resistance calibration. The difference in resistance between the two definitions was 0.84 mΩ, of which 0.6 mΩ was due to contact resistance of the BPO connectors. The frequency characteristics of each chip-resistor were corrected by adjusting the potential of a special built-in screen. The characteristics of the resistance standards are shown in **Table 1**.

**Table 1** Characteristics of ac resistors for MWB

| Characteristics | Nominal value | |
|---|---|---|
| | 1 kΩ | 10 kΩ |
| $R_{1\,\mathrm{kHz}} - R_{\mathrm{dc}}$, μΩ/Ω | 0 ± 0.2 | 0.3 ± 0.2 |
| Temperature coefficient, (μΩ/Ω)/K | 1.3 ± 0.2 | 1.6 ± 0.2 |
| Time constant at 1 kHz, nS | 0 ± 1 | -4 ± 2 |

### 3.4 Substitution Resistors

Two variable resistors for substitution with two terminal, three terminal, or 2T-P definition were manufactured to substitute for the 10 and 100 mH standard inductors to be measured in accordance with the method of "zero substitution". The range of nominal resistance values should be sufficient to allow measurement of the standard inductor. The resolution of the required resistance was determined by the allowable degree of the residual unbalance of the bridge when balanced using the substitution resistor. This unbalance was eliminated by adjusting the resistance of $R_3$, to keep the shunt capacitance less than 0.001%. The respective variation of $R_3$ did not exceed 0.005%, thus the resolution was at least 0.005%. The residual inductance of the substitution resistor needed to be as small as possible, and it was required to have a known sufficient accuracy. The substitution resistors were adjustable over the range of 7.8 Ω to 9.1 Ω with a resolution of 0.8 mΩ for the 10 mH inductor, and 68 Ω to 92 Ω with a resolution of 8 mΩ for the 100 mH inductor. These consisted of a combination of fixed resistors and a multi-turn variable resistor, and were equipped with terminals similar to those of the standard inductor. The residual inductance of the substitution resistors was measured by comparing three resistors. The inductance of the resistors was calculated based on their geometry. Two of these were a fixed and a variable bifilar resistor and the third was a commercial small-size cylindrical resistor. The calculated results agreed to within ±10 nH for an 8.25 Ω resistor and ±20 nH for an 82.80 Ω resistor.

### 3.5 Standard Inductor

An inductor (GR1482-H) was placed in the thermostat and maintained at 28°C. The temperature fluctuation in the thermostat did not exceed ±2 mK in a room maintained within ±0.4 K. The drift of the inductance was 2.3 μH/H during the first 12 months after the inductor had been placed into the thermostat.

## 4. Investigation

An experimental model using the CIS consisting of a generator (GR1316), a detector (GR 1238) and a variable capacitor (GR 1422 CL) was investigated for one year. The instability of the 10 mH standard inductor placed in the thermostat was 2.3 (μH/H)/y. The instability of the 10 nF standard capacitor was 0.61 μF/F, and the instabilities of the standard resistors were 0.2 (μΩ/Ω)/y and 0.3 (μΩ/Ω)/y for the 1 kΩ resistors, and less than 0.1 (μΩ/Ω)/y for the 10 kΩ resistor. In the measurements taken at frequencies of 1 and 1.6 kHz, the balance was established by cycling the balancing operations of the main bridge and the two auxiliary circuits. Convergence of the bridge was very fast, taking only 3-4 min to establish the balance. The balance was maintained constant over a period of several hours at room temperature within ±0.2°C. The bridge was delivered to VNIIM for a trial comparison to demonstrate the possibility of using the bridge as a part of a transportable standard. The 10 and 100 mH VNIIM standards (both without a thermostat) were measured at a frequency of 1 kHz using the two installations: the VNIIM primary standard (EI-2) and our CIS with two or three terminal definitions of the inductance standard. The design of the VNIIM inductance standards is analogous to that of the KRISS inductor. The combined uncertainty of inductance measurements using the VNIIM equipment was $2.4\times10^{-6}$ [CCEM-K3]. The measured results of the 10 mH standard using the two installations with a three terminal definition differed from each other by 30 nH. The disagreement in the measured results of the 100 mH standard with a three terminal definition did not exceed $1.2\times10^{-6}$ when the same substitution resistor was used and when additional screening for the terminals of the standard and the bridge were employed.

## 5. Uncertainty

The uncertainty in the inductance measurements was evaluated using a mathematical model of the measurements, described in (1). The results of our investigations demonstrated that a number of the quantities are negligible by the zero-substitution method. These quantities show that: (i) the relative influence combined with time constants $\tau_i$ and loss angle $\delta_3$, secondary parameters of the standard resistors and the capacitor, does not exceed $0.03\times10^{-6}$ up to a maximum frequency of 3 kHz; (ii) the change in impedance connected in series with the inductance standard at arm 1, which comes from the change of contact resistance of the terminals in arm 1 (smaller than 0.5 mΩ), does not exceed $0.001\times10^{-6}$; and (iii) the instability and measurement uncertainty from changes in frequency change does not exceed $0.001\times10^{-6}$. The uncertainty budget is illustrated in **Table 2**.

Our analysis also takes into consideration quantities that are not directly included in the model, but these come from the influences of the input quantities of the model or the characteristics of the bridge balancing process. Thus, we took into account quantities in the uncertainty value corresponding to standards as follows: (i) the influence of temperature fluctuations (±0.2°C) on the resistance and capacitance standards; (ii) the accuracy of the determination the frequency characteristics; (iii) the variation of impedance of the 2-TP definition with the definition of the bridge; and (iv) the uncertainty of the correction for the difference in resistance for the four terminal and 2T-P definitions. However, the effect of incomplete balancing of the two auxiliary circuits (source and detector balance), the finite sensitivity of the main balance detector, and the resolution of the bridge readouts were introduced into the model described by Equation (1).

The dominating sources of uncertainty in Table II are: (i) from the inductance of the substitution resistor ($1\times10^{-6}$); (ii) from the resistance of the 1 kΩ ac standard in the 10 mH measurements ($0.8\times10^{-6}$); (iii) from the stray capacitance of the inductance terminals ($0.8\times10^{-6}$); and (iv) from the temperature instability of the inductance standard in the 100 mH measurements ($0.6\times10^{-6}$).

**Table 2** Uncertainty budgets for compact inductance standard

| No | Source of uncertainty | Type | Relative standard uncertainty in $10^{-6}$ | | Comments |
|---|---|---|---|---|---|
| | | | 10 mH | 100 mH | |
| 1 | Repeatability | A | 0.10 | 0.08 | $n = 15$ |
| 2 | 10 nF standard | B | 0.80 | 0.80 | Including frequency dependence |
| 3 | Variable capacitor | B | 0.20 | 0.20 | Calibration |
| 4 | 1 kΩ standard | B | 0.80 | 0.55 | Including contacts variation |
| 5 | 10 kΩ standard | B | - | 0.42 | |
| 6 | Stray capacitance of the inductance terminals | B | 0.08 | 0.80 | $\Delta C_S$=0.2 pF at 1 kHz |
| 7 | Limited sensitivity of the main balance | B | 0.10 | 0.10 | |
| 8 | Source and detector balance | B | 0.20 | 0.20 | Combined effect |
| 9 | Inductance of the substitution resistor | B | 1.00 | 0.20 | |
| 10 | Inductance standard (temperature instability) | B | 0.05 | $0.6^*$ | 100 mH without a thermostat |
| Relative combined standard uncertainty | | | 1.54 | 1.50 | |
| Relative expanded uncertainty | | | 3.1 | 3.0 | $k = 2$ |

The measurement uncertainty of the 10 mH standard can be reduced by additional investigation of the substitution resistor's inductance, which can decrease its uncertainty by half (i.e., down to 5 nH). However, the variation of contact resistance of the 1 kΩ ac resistors (0.4 mΩ) is an irreducible source of uncertainty at the 2T-P definition. The accuracy of the 100 mH measurements can be improved significantly by using additional screens between the two terminals of the inductance standard to be measured, which is placed in a thermostat like the 10 mH standard.

## 6. Conclusion

A new compact and transportable inductance standard has been developed at KRISS. It consists of both a MWB comprising a standard capacitor and two standard resistors, and a standard inductor placed in a thermostat. It can be used for intercomparisons among NMIs. The investigations and a trial intercomparison between KRISS and VNIIM have shown that the reproduction uncertainty for inductances of 10 mH and 100 mH was within the limits of (1-3) μH/H at frequencies of 1 kHz and 1.6 kHz. A newly fabricated inductance standard is being used as a national primary standard of inductance unit at KRISS.

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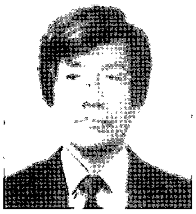

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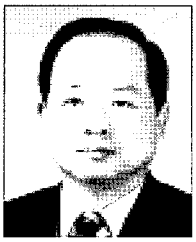

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