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Influence of Adaptor on the Calibration of Inductance Standards

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Abstract – Influence of the adaptors on the calibration of 100 μH inductance standard was studied as a function of torque, applied when tightening the standard inductor terminal with the adaptor. Two different homemade adaptors of BPO gold-plated brass (BPO-Au) and banana-copper (BN-Cu) were made for the connection between the LCR meter and the inductance standard. The measured inductance (L) of the standard inductor and the contact resistance (R_C) between the adaptor and the standard inductor terminal showed exponential decreases against the torque increase from 25 cN·m to 150 cN·m. The measured L and the calculated equivalence series resistance (R_S) were dependent on the adaptor type as well as on the R_C. The results of the adaptor analysis imply that the BPO-Au adaptor with the lower R_C is more suitable for the inductance calibration. The calculated inductance of 99.956 μH corrected by subtraction of the adaptor inductance and the contact resistance contributions from the measured value using the BPO-Au adaptor agreed well with the certificate (99.948 μH) of the PTB within the measurement uncertainty of 140 μH/H.

Keywords: Inductance calibration, LCR meter, Adaptor, Contact resistance

1. Introduction

An improper contact between the test leads of a measuring instrument like the LCR meter and the terminals of a standard inductor can considerably affect the precision measurements of the inductance. Also, the adaptor used between the instrument test leads and the inductance standard terminals can make a measurable contribution to the total impedance of the standard inductor [1, 2]. If the inductance value is 100 μH for instance, the contact resistance of mΩ order is very significant since its impedance is less than 1 Ω (0.63 Ω at the frequency of 1 kHz). It is certain that the contact resistance can lead to a considerable effect on the precision measurements of the low value inductance standards (<1 mH) [3, 4]. Hence, a special care should be taken for keeping the contact resistance small other than reducing the series resistance by the test leads and making the surrounding free from metal, other conductors, and operator hands [5].

The standard inductors of GenRad 1482 type are widely used in the national metrology laboratories as low-frequency inductance standards due to its long-term stability, low-temperature coefficient, low internal series resistance, and low-quality factors. The GenRad 1482 type standard inductors have three binding post terminals, two for the inductor leads and the third connected to the case. Among them, the 100 μH standard inductor has three additional terminals with a shorting bar for the connection error compensation [6].

For the calibration of inductance standards, a common method is the substitution using an LCR meter. However, most LCR meters have four terminals, so an adaptor is required between the LCR meter and the standard inductor connection. For that reason, we designed two different types of adaptors: BPO gold-plated brass and a combination of a banana plug with a copper-based metal block. Laboratories undertaking the highest accuracy measurements usually employ the British Post Office (BPO) connector for its good contact [7, 8]. Yet, the GenRad 1482 type standard inductors have binding post (banana) type terminals, and most LCR meters have BCN type terminals. In this study, we compared two different types of the homemade adaptors for their influences on the contact resistance, equivalent series resistance, and inductance measurements. Also, the adaptor influences on the calibration of the 100 μH standard inductor were investigated in conjunction with the torque applied to tighten the adaptor with the inductance standard terminals.

2. Experiments

The inductance (L) of the 100 μH standard inductor (GenRad 1482-B type) was measured using an LCR meter (QuadTech 7600). For the connection of the inductance standard to the LCR meter, two homemade adaptors were used as shown in Fig. 1: BPO plug with gold-plated brass adapter (BPO-Au) and banana plug with copper adaptor (BN-Cu). For the BPO-Au adaptor, 2 units of Fig. 1a are used, and for the BN-Cu adaptor, 4 units of the banana plugs (Fig. 1b1) are used together with the 2 units of Fig.

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1b2 as shown in Fig. 2. Two different torque drivers, N6LTDK for (5~60) cN·m and N20LTDK for (40~200) cN·m were used to control the torque (τ) between the adaptor and the standard inductor terminals. The minimum incremental torque was 0.5 cN·m and 1 cN·m for the N6LTDK and N20LTDK, respectively. The accuracy of the torque was ±3 % of the setting value over the whole range. The contact resistance (R_C) between the adaptor and the standard inductor terminals was measured with HIOKI BT3562 Battery HiTester using a 4-point probe method. All the measurements of R_C and L were obtained at a frequency of 1 kHz. The laboratory environment was controlled at (23 ±1 °C) temperature condition, and the contact surfaces were kept clean from dust and oxides.

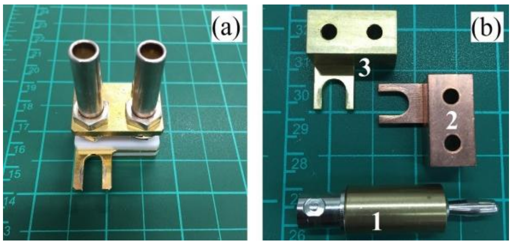

Fig. 1. Homemade adaptors: (a) BPO plug with gold-plated brass (BPO-Au) and (b1) banana plug with (b2) copper block (BN-Cu) and (b3) brass block (BN-BS)

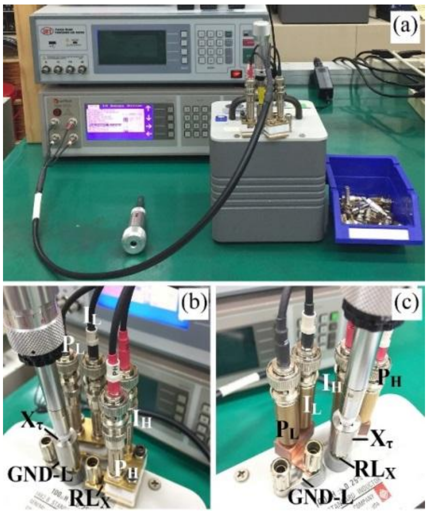

Fig. 2. (a) Measurement setup for the inductance L measurements using the LCR meter and the adaptors of (b) BPO-Au and (c) BN-Cu. I_H(I_L): current high(low), P_H(P_L): potential high(low), GND-L: ground shorting bar, RL_X: measurement plane, and X_τ: torque driver

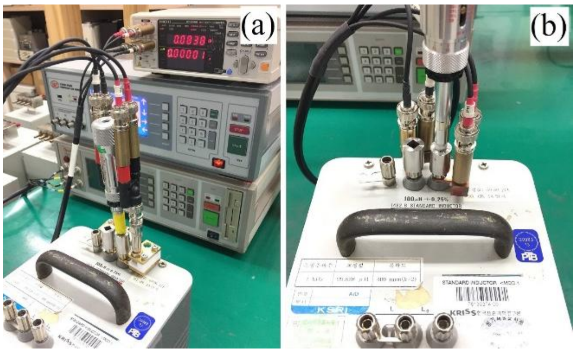

Fig. 3. Measurement setup for the contact resistance R_C measurements using HIOKI BT3562 Battery HiTester and the adaptors of (a) BPO-Au and (b) BN-Cu

Figure 2 and 3 show measurement setups for the L (Fig. 2) and the R_C (Fig. 3). The potential terminals (P_H, P_L) of the adaptor directly make contact with the binding post terminals of the inductance standard. The inductor case was connected to the low terminal using a ground shorting bar (GND-L). The measurement plane (contact area between the adaptors and the binding terminals of the inductor) RL_X is depicted in Fig. 2. The tightening force was applied using the torque driver X_τ

3. Results

Figure 4 shows the measurement results of (a) L, (b) quality factor Q, and (c) R_C for the two adaptors of BPO-Au and BN-Cu as a function of the torque (τ) from 25 cN·m to 150 cN·m. For the BPO-Au adaptor, the L changed by 9.3 nH from 100.1327 μH to 100.1234 μH while the R_C was decreased by 0.163 mΩ from 3.464 mΩ to 3.301 mΩ over the whole torque range of (25 ~ 150) cN·m. In case of the BN-Cu adaptor, the measured L and R_C were

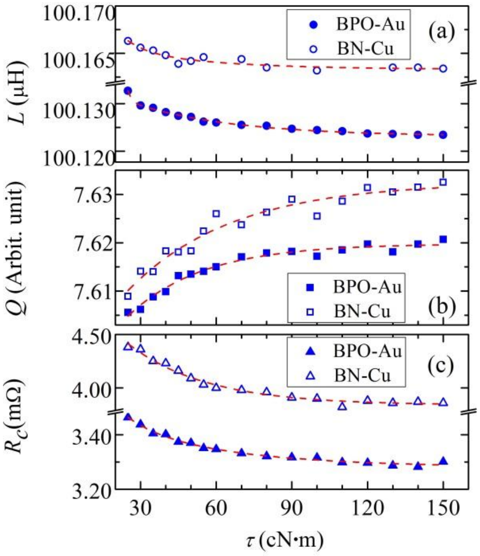

Fig. 4. Measured (a) inductance L, (b) quality factor Q, and (c) contact resistance R_C for two different adaptors of BPO-Au (solid symbols) and BN-Cu (open symbols) as a function of torque τ. Dashed lines are fitted curves using Eq. 1 (s. text)

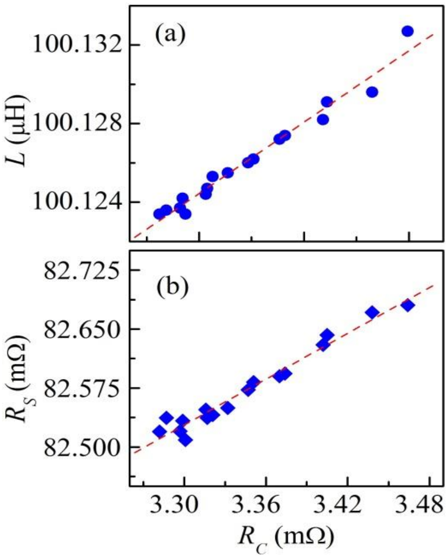

Fig. 5. (a) Measured inductance L and (b) calculated equivalent series resistance R_S from the measured quality factor Q with BPO-Au adaptor as a function of contact resistance R_C. Dashed lines are linearly fitted lines

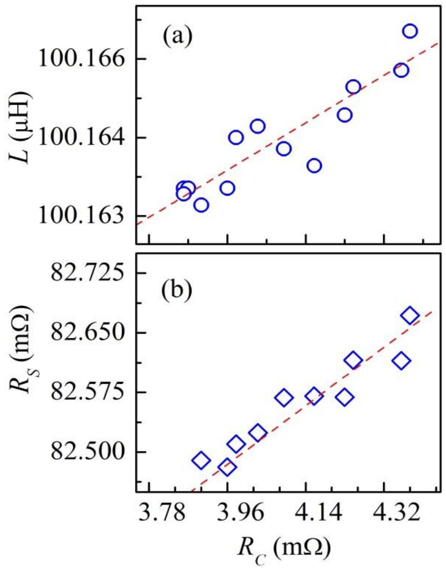

Fig. 6. (a) Measured inductance L and (b) calculated equivalent series resistance R_S from the measured quality factor Q with BN-Cu adaptor as a function of contact resistance R_C. Dashed lines are linearly fitted lines

generally about (36~40) nH and (0.9~0.57) mΩ, higher than those of the BPO-Au adaptor over the whole torque range. It is evident from the results that not only the L (Fig. 4a) but also the R_C (Fig. 4c) of the standard inductor is significantly dependent on the adaptor types. The hand force applied by the operator was found to be around 15 cN·m~30 cN·m while the optimum τ range where L and R_C values are constant within the measurement uncertainties was estimated to be 100 cN·m ~ 150 cN·m in this experiment.

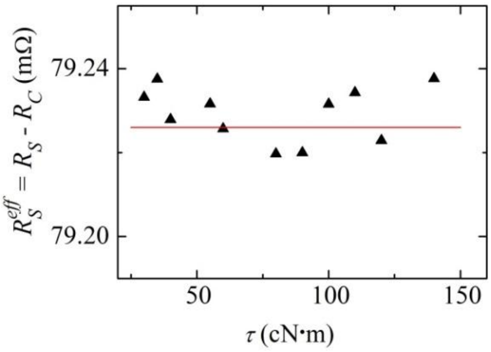

Fig. 7. The effective equivalent series resistance values of experimentally estimated (solid triangle) and reference from the calibration certificate (solid line)

Fig. 5 and 6 show the measured L and calculated equivalent series resistance (ESR) R_S as a function of the R_C for the two adaptors of BPO-Au and BN-Cu. Not only L (Fig. 5a and 6a) but also R_S (Fig. 5b and 6b) varied linearly against the R_C.

The effective R_S, defined as $R_S^{eff} = R_S - R_C$, was estimated to be about 79.23 mΩ which well matches with the calibration certificate value of 80 mΩ provided by the manufacturer [6] as plotted in Fig. 7.

4. Discussions

4.1. Correlation between the inductance and the contact resistance

In order to investigate the relationship between the measured L and R_C, the measured data was fitted using an exponential equation below:

$$y = y_0 + A \cdot \exp(-\tau), \tag{1}$$

where y and y_0 are L or R_C and L_0 or R_{C0} for $\tau = 0$, respectively, and A is the fitting parameter for the amplitude of the measurement values.

It is interesting to notice that the decrement rates of τ_L = 28 μH/cN·m for the L and τ_{RC} = 31 mΩ/cN·m for the R_C are nearly the same within the fitting uncertainty of ±3 cN·m. The correlation leads to a linear dependence (dashed line) between L and R_C as shown in Fig. 5a and 6a. The L linearly changes against R_C with a slope of 47 nH/mΩ, and from the gradient, we can estimate L_0 with $R_C = 0$.

The calculated value of L_0 = 99.968 μH for the BPO-Au adaptor shows a deviation from the PTB (*Physikalisch-Technische Bundesanstalt*) calibration certificate value of 99.948 μH by about 200 μH/H. On the other hand, the calculated value of L_0 for the BN-Cu adaptor was estimated to be 100.145 μH, showing a large deviation from the reference value by about 0.197 μH. Such a difference between the two adaptors comes from the influence of the adaptor lumped compónts (inductance L_{ADP}, series resistance R_{ADP}, and capacitance C_{ADP}) which will be explained in the following section.

In contrast to the exponential behavior of the L and R_C vs. τ, the measured quality factor Q, defined as a ratio between L and ESR, logarithmically increased with the increasing torque as shown in Fig. 4b. The ESR, calculated from the measured Q is determined mainly by the ohmic resistance of the inductor windings.

To understand the relation between the measured L and the R_C, an equivalent circuit of the inductance standard was considered as shown in Fig. 8. A relative change in R_C caused by the applied torque was taken into account as well. The parallel capacitive component was neglected for simplicity, because the measurement conditions of the system were not changed during inductance measurements.

For the inductance measurement, a digital LCR meter measures the current I flowing through the reactance X_L of the inductance standard with voltage across it V_L and phase between them. X_L is defined as $X_L = 2\pi fL$. While an ideal inductor impedance can be defined as $|Z_L|^2 = R_S^2 + X_L^2$, the total impedance can be defined as $|Z_{\mathrm{tot}}|^2 = (R_{\mathrm{Vp}} + R_C + R_S)^2 + X_L^2$, taking into account the LCR meter source resistance and the contact resistance between the adaptor and the inductance standard terminal. The LCR meter has a constant source resistance R_{Vp} of 25 Ω [7]. The inductance variation ΔL caused by the R_C can be calculated as follows:

The impedance of the inductor $|Z_L|$ with the R_C is defined as effective impedance $|Z_{\mathrm{eff}}|$

$$|Z_{\mathrm{eff}}|^2 = (R_S + R_C)^2 + X_L^2. \tag{2}$$

The voltage V_{eff} appeared across the $|Z|_{\mathrm{eff}}$ with the setting voltage V_p of the LCR meter

$$V_{\mathrm{eff}} = \frac{|Z_{\mathrm{eff}}|}{|Z_{\mathrm{tot}}|} \cdot V_p, \tag{3}$$

and the following current I_{eff} flowing through the $|Z|_{\mathrm{eff}}$ is

$$I_{\mathrm{eff}} = \frac{V_{\mathrm{eff}}}{|Z_{\mathrm{eff}}|}. \tag{4}$$

The voltage V_L across the reactance X_L is

$$I_{\mathrm{eff}} \cdot X_L = V_{\mathrm{eff}} - I_R \cdot (R_C + R_S). \tag{5}$$

where I_R is

$$I_R = \frac{V_{\mathrm{eff}} - I_{\mathrm{eff}} \cdot X_L}{|Z|_{\mathrm{tot}}}. \tag{6}$$

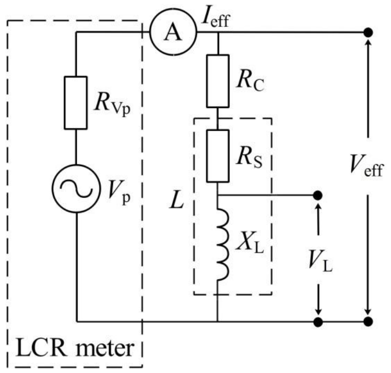

Fig. 8. Schematic circuit diagram for the inductance measurement. L is the inductance consisting of the inductor reactance X_L and equivalent series resistance R_S. V_p is a test voltage of LCR meter, R_{Vp} is a constant source resistance, and I_{eff} current flowing through the system including the R_C. V_{eff} and V_L are the effective voltages across the system and the inductor reactance, respectively

From Eq. (5), the X_L can be calculated:

$$X_L = \frac{V_{\mathrm{eff}} - I_R \cdot (R_C + R_S)}{I_{\mathrm{eff}}}. \tag{7}$$

The calculated current variation ΔI_R caused by the change of the $R_{C1} = 3.301$ mΩ and $R_{C2} = 3.464$ mΩ is about 1.2×10^{-8} A and $\Delta X_L \approx 66.2$ μΩ. The ΔL derived from the contact resistance variations, R_{C1} and R_{C2}, is about 10.5 nH and shows a good agreement with the calculated one from the measured value 9.3 nH in section 3.

4.2 Contribution of the adaptor lumped components to the inductance measurement

To study the effects of the adaptor lumped components, inductance L_{ADP}, resistance R_{ADP} and capacitance C_{ADP} of each adaptor were measured using the same LCR meter. Fig. 9 shows measurement setup for the C_{ADP} with an external capacitor C_{ext}. Inset shows an equivalent circuit diagram for the measurement setup. Actually, measurements of the lumped components are sensitive to the external conditions. Therefore, an extra grounded metallic box was used for shielding of electromagnetic interferences and reliable measurements (Fig. 9).

Table 1 shows the measured lumped component values for each adaptor. The L_{ADP} of the BN-Cu adaptor was about 0.17 μH, explaining the large deviation of 0.2 μH in the inductance value discussed in section 4.1.

Table 1. Measured lumped component values for each adaptor

	L_{ADP} (μH)	R_{ADP} (mΩ)	C_{ADP} (pF)
BPO-Au	0.012	4.2	11.1
BN-Cu	0.166	3.5	5.5

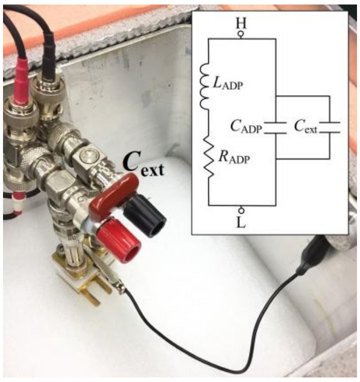

Fig. 9. Measurement setup for the stray capacitance effect C_{ADP} of the adaptor adaptor located in a grounded metallic shielding box. External capacitor C_{ext} was attached parallel to the electrodes. Inset is a equivalent circuit diagram for the measurement

Table 2. Uncertainty budget for the inductance measurements using BPO-Au and BN-Cu adaptors, respectively

Quantity	Distribution	Standard uncertainty (μH/H)	
		BPO-Au	BN-Cu
Repeatability	Normal A	40	60
Uncertainty of the LCR meter	Rectangular B	55	55
Temperature coefficient of the standard inductor	Rectangular B	25	25
Combined uncertainty (k = 1)		75	85

Further experimental investigation was performed to estimate the C_{ADP} effect by applying an additional C_{ext} between the two electrodes (Fig. 9). The inductance of the adaptor was measured by increasing C_{ext} values from 0.1 μF to 1 μF. The adaptor inductance linearly increased with the C_{ext} but the increment rate of about 56 nH/μF is negligible within the capacitance value 10 pF. This implies that the stray capacitance of the adaptor barely influences the inductance measurements [8, 9]. The calculated inductance of 99.956 μH subtracted by the contribution of the BPO-Au adaptor inductance of 0.012 μF and the contact resistance from the measured L value agreed well with the certificate (99.948 μH) of the PTB within the measurement uncertainty of 140 μH/H.

4.3. Uncertainty

Table 2 presents the measurement uncertainty budget for the two adaptors of BPO-Au and BN-Cu. The main uncertainty factors are the LCR meter uncertainty and the temperature coefficient of the standard inductor. The LCR meter uncertainty was evaluated using an inductance standard as a reference, taking its uncertainty of calibration, long-term stability, and temperature coefficient and also the resolution and the short-term stability of the LCR meter. The temperature coefficient of inductance standard is 45 × 10^{-6}/°C also evaluated by ourselves. The temperature variation of the laboratory was ±1 °C.

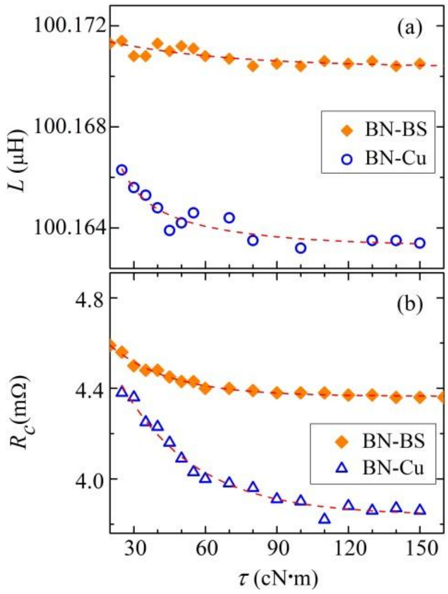

Fig. 10. Measured (a) inductance L and (b) contact resistance R_C for two different adaptor materials of BN-BS (solid symbols) and BN-Cu (open symbols) as a function of torque τ. Dashed lines are fitted curves using Eq. 1 (s. text)

The uncertainty budget shows the measurement repeatablity is dependent on the type of adaptors. The reason for the difference in the type A uncertainty is mainly due to reproducability of the measurements. It should be mentioned that the connection of the BPO-Au adaptor shows more stable contact property than the BN-Cu adaptor where the contact is not reliable and not well defined for every measurement [10].

4.4 Adaptor material dependence on the contact resistance

It is worth to mention that the R_C between the adaptor and the standard inductor terminal is also affected by the adaptor material. It was evidenced by the comparison of L and R_C measured as a function of τ using the same banana plug adaptor made of different materials such as copper (BN-Cu) and brass (BN-BS) (Fig. 1b3).

Fig. 10 clearly shows different characteristics of L and R_C for the two different adaptor materials of brass (solid symbols) and copper (open symbols), respectively. The L values obtained by the BN-BS adaptor are much larger than those measured using the BN-Cu adaptor, whereas the decreasing behaviors of L and R_C obtained by using the BN-BS adaptor against the increasing torque are rather smoother than those obtained by using the BN-Cu adaptor. Wenner et al. reported that the contact resistance decreases as the torque increases and becomes nearly constant as the torque approaches the yield point of the material [11]. As expected, the contact resistance is lower for those materials having higher electrical conductivities.

4.5 Comparison with the 6-terminal measurement

As mentioned at the beginning, 100 µH inductance standard (GenRad 1482-B type) is equipped with 3 additional supplementary terminals [4,6] for the elimination of parasitic influences such as stray capacitance, lead impedance, and contact resistance, etc. Therefore, we also conducted the 6 terminal measurements and compared with the 3 terminal measurements done so far. The 6 terminal measurement value of 99.950 µH shows a good agreement with the 3 terminal measurement value of 99.956 µH, obtained with subtraction of 0.012 µH from the L_0 = 99.968 µH.

The adaptor analysis done in this study would not be needed for low value inductors, e.g. $L \leq 100$ µH with the supplementary terminals. However, it may be required for those inductance standards without the supplementary terminals, e.g. 1 mH and 10 mH, in order to keep the measurement uncertainty small.

According to the adaptor analysis above, the BPO-Au adaptor results in the inductance change of 10.5 nH for the R_C increment. Then, for 1 mH and 10 mH, the adaptor contributions are estimated to be about 53 % of 20 µH/H and 21 % of 5 µH/H, respectively.

5. Conclusions

In order to calibrate an inductance standard using an LCR meter, we designed two different types of the adaptor for the connection between the LCR meter and the inductance standards. The contact resistance R_C between each adaptor and the standard inductor terminals and the inductance L and quality factor Q of the 100 µH standard inductor were measured as a function of torque from 25 cN·m to 150 cN·m. All the measured quantities were dependent on the adaptor type and the torque applied for the tightening of the adaptor to the standard inductor terminals. The measured L and the equivalent series resistance ESR apparently showed a linear dependency on the adaptor R_C, so the measured L could be corrected by subtracting the R_C contribution, obtained from the linear fitting of the measurement data. Furthermore, although the LCR meter measurement setting was in the inductance mode the contact resistance of the adaptor considerably influenced the inductance measurement. The adaptor analysis results imply that the BPO-Au adaptor with the lower R_C is more suitable for the precision inductance measurement when compared with the BN-Cu adaptor with poor contact property. The calculated L value, where the contributions of the inductance and the contact resistance of the adaptor were subtracted from the measured L using the BPO-Au adaptor, shows a good agreement with the certificate value of the PTB within the measurement uncertainty.

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References

[1] B. P. Kibble, “For Terminal-Pair to Anything Else,” National Physical Laboratory, UK, 1999.
[2] B. P. Kibble and G. H. Rayner, Coaxial AC Bridges, Adam Hilger Ltd, UK: 1984, pp. 4, pp. 83-86.
[3] The General Radio Experimenter, “A Close Look at Connection Errors in Capacitance Measurements,” vol. 33, no. 7, 1959.
[4] The General Radio Experimenter, “Connection Errors in Inductance Measurement,” vol. 34, no. 10, 1960.
[5] QuadTech, “Building the Perfect Component Test Fixture,” *Application Note*, no. 035094, 2000.
[6] IET LABS, INC., http://www.ietlabs.com/ 1482.html, 2003.
[7] QuadTech, “What Voltage and Current is Applied to the Unknown,” *Application Note*, no. 035050/A3, 2003.
[8] QuadTech, “Series & Parallel Impedance Parameters and Equivalent Circuits,” *Application Note*, no. 035010, 2003.
[9] QuadTech, “A Guide to LCR Measurements,” Application Note no. 035001, 2003.
[10] M. K. Dewi, D. B. Kim and W. S. Kim, “Influence of Adaptor on the calibration of Inductance Standards,” presented at 21st IMEKO TC4 International Symposium, 2016.
[11] F. Wenner. G. W. Nusbaum, B. C. Cruickshanks, “Note on the Electrical Resistance of Contacts between Nuts and Bolts, Bureau of Standards,” *in Journals of Research*, 1930.

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