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Influence of Adaptor on the Calibration of Inductance Standards

Dewi Mohd Kassim[1,2,3], Dan Bee Kim[1], and Wan-Seop Kim[1,2]

[1]*Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Rep. of Korea*
ws2kim@kriss.re.kr

[2]*University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Rep. of Korea*

[3]*National Metrology Institute of Malaysia, Lot PT 4803 Bdr Baru Salak Tinggi, 43900 Sepang, Selangor Malaysia*

***Abstract* — Influence of the adaptor on the calibration of 100 µH inductance standard has been studied using two different homemade adaptors of BPO gold-plated brass (BPO-Au) and banana-copper (BN-Cu) as a function of torque. The inductance (L) and the contact resistance (R_C) showed an exponential decrease against the increasing torque from 25 cN·m to 150 cN·m. The measured L and the calculated equivalence series resistance are dependent on the type of adaptors as well as the R_C. The analysis of R_C and measurement uncertainty of L implies that the BPO-Au adaptor with low R_C is suitable for the calibration of inductance. The measured L obtained using BPO-Au and subtracted by the R_C agreed well with the certificate value of the PTB within the measurement uncertainty of 140 µH/H. In addition, the calculated inductance of the adaptors shows influence of the lumped components, stray capacitance and series resistance, on the measurements of standard inductors.**

***Keywords* – Adaptor, contact resistance, inductance standard, torque, quality factor**

I. INTRODUCTION

An improper contact between the test leads of a measuring instrument and the terminals of a standard inductor can considerably affect precision measurements of inductance standards [1][2]. In particular, if the inductance value is lower than 100 µH, the effect of the contact resistance can be very significant due to the fact that its impedance is lower than 1 Ω (0.63 Ω at the frequency of 1 kHz) and its contact resistance R_C is in the order of mΩ [3]. Therefore, it is clear that only a little deviation in the contact resistance can lead to a considerable effect on the precision measurements of the inductance standards.

The standard inductors, GenRad 1482 type, are widely used in the national metrology laboratories as a low frequency reference due to its long-term stability, low temperature coefficient, low internal series resistance, and low Q-factors. The GenRad 1482 type standard inductors have three binding post terminals, two for the inductor leads and the third connected to the case [4]. For the calibration of the inductance standards, a common method is the substitution using a LCR meter. However, most LCR meters have four terminals, so an adapter is needed between the LCR meter test leads and the inductor terminals.

In this study, we designed two different types of adaptors, BPO gold-plated brass (BPO-Au) and banana-copper (BN-Cu), for the calibration of the inductance standards and studied the influence of the adaptor on the calibration of the 100 µH standard inductor in conjunction with various torque values. The measurements results show the contact resistance and the measured inductance are strongly dependent on the type of adaptor and torque applied for tightening of the binding post of the inductor. Hence, we report the contribution of the adaptors to the contact resistance, equivalent series resistance and inductance measurements.

II. EXPERIMENTS

The contact resistance (R_C) was measured using HIOKI BT3562 HiTester using a 4-point probe method. The inductance (L) of the 100 µH standard inductor (GenRad 1482 type) was measured using a LCR meter (QuadTech 7600). Two homemade adaptors, BPO plug with gold-plated brass adapter (BPO-Au) and banana plug with adapter made from copper (BN-Cu) as shown in Fig. 1

were applied for the R_C and the L measurements. Two different torque drivers, N6LTDK for (5 ~ 60) cN·m and N20LTDK for (40 ~ 200) cN·m were used to control the torque between the adaptor and the inductor terminals. The minimum incremental torque was 0.5 cN·m and 1 cN·m for the N6LTDK and N20LTDK, respectively. Accuracy of the torque was ±3 % of the setting value over the full range. All the measurements of R_C and L were obtained at a frequency of 1 kHz.

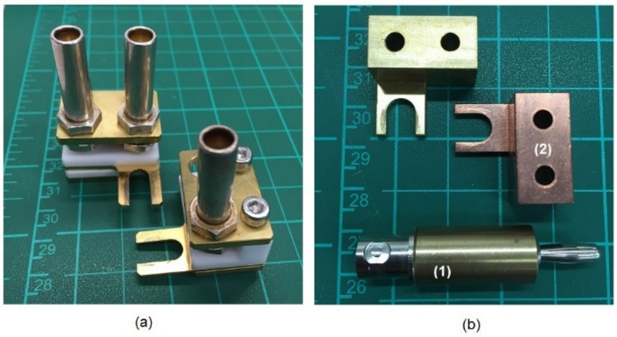

Fig. 1. Homemade adaptors (a) BPO plug with gold-plated brass (BPO-Au) (b) Banana plug (1) with copper (2) adaptor (BN-Cu).

Fig. 2 shows a measurement plane (shaded) of the adaptor for the contact resistance and inductance measurements, respectively. The potential side of the adaptor directly makes a contact with the binding post terminal of the inductance standards.

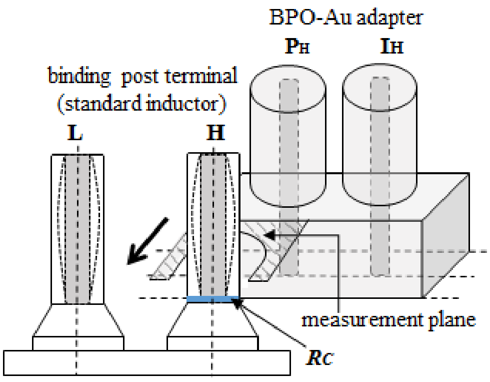

Fig. 2. Measurement plane (shaded) of the adaptor for the contact resistance and inductance measurements, respectively.

III. RESULTS AND DISCUSSIONS

Fig. 3 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. It is obvious that not only the inductance values (Fig. 3(a)) but also the contact resistances (Fig. 3(b)) of the standard inductor are significantly different and strongly dependent upon the adaptor types used for the measurements. But the optimum τ range for the L and R_C, where L and R_C values are constant within the measurement uncertainties, is nearly the same and estimated to be 90 cN·m ~ 150 cN·m.

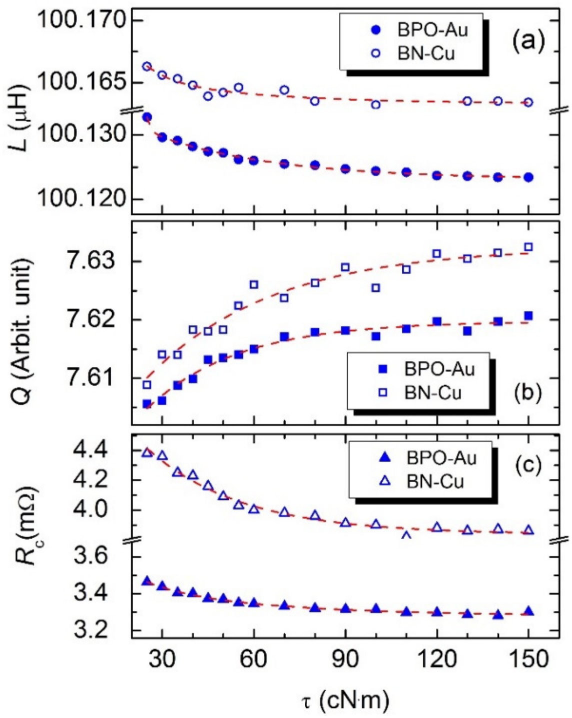

Fig. 3. Measured (a) inductance L, (b) quality factor Q, and (c) contact resistance R_C for the two different adaptors of BPO-Au (solid symbols) and banana-copper (BN-Cu, open symbols) as a function of torque τ. Dashed lines are fitting curves using eq. (1) (s. text).

In the case of the BPO-Au adaptor, the inductance changed by 9.3 nH from 100.1327 μH to 100.1234 μH while the contact resistance was decreased by 0.163 mΩ from 3.364 mΩ to 3.301 mΩ over the whole torque range of (25 ~ 150) cN·m. The measured R_C and L can be well fitted using an exponential equation below:

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

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

It is worth to mention that the decrement rates of $t_L = 28$ cN·m for the inductance and $t_{SC} = 31$ cN·m for the contact resistance are nearly the same within the fitting uncertainty of ±3 cN·m. This leads to a linear dependence (dashed line) between L and R_C as shown in Fig. 4(a) and (c). The L linearly changes by R_C with a slope of 47 nH/mΩ.

From the slope of L vs. R_C, we can calculate L_0 with R_C = 0. The calculated value of L_0 = 99.968 μH shows a deviation by about 200 μH/H from the certificate value, L_{cert} of 99.948 μH calibrated by the PTB.

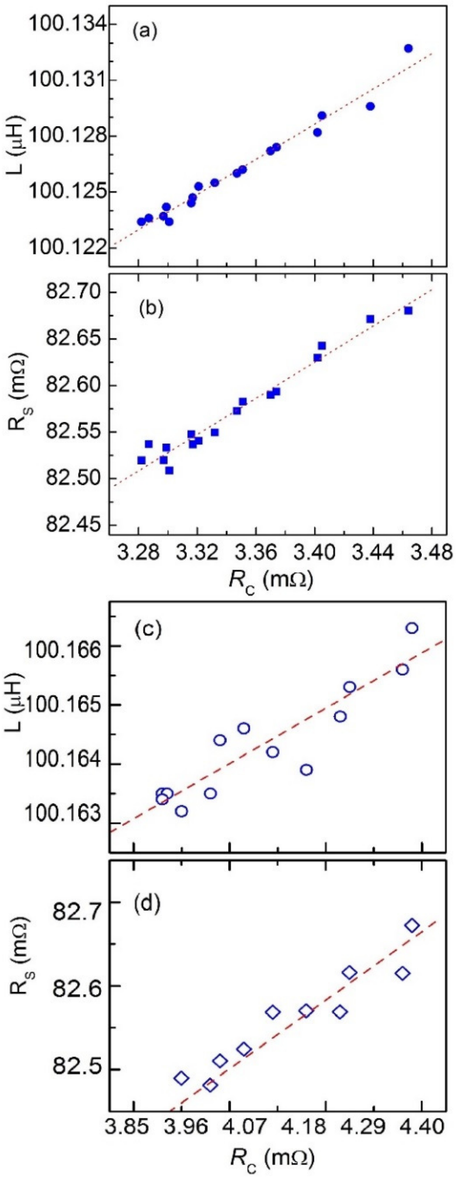

Fig. 4. Measured inductance L (a: BPO-Au adaptor, c: BN-Cu adaptor) and calculated series resistance R_S (b: BPO-Au adaptor, d: BN-Cu adaptor) as a function of contact resistance R_C. Dashed lines are linear fitting lines.

For the BN-Cu adaptor, the measured inductance in Fig. 3(a) and the contact resistance in Fig. 3(c) are generally about 36 ~ 40 nH and 0.9 ~ 0.57 mΩ higher than those of the BPO-Au adaptor over the whole torque range. The measured L values also show a linear dependence on R_C. However, the fitting value of L_0 estimated to be 100.145 μH shows a large deviation from the reference value. This is due to influence of the lumped components (inductance L_{ADP}, series resistance, R_{ADP} and capacitance, C_{ADP}) of the adaptor, elucidated below.

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 equivalent series resistance (ESR) R_S, logarithmically increases with the increasing torque as shown in Fig. 3(b). The ESR calculated from the measured quality factor is mainly determined by the ohmic resistance of the inductor windings.

Fig. 4 shows measured inductance and calculated ESR as a function of the R_C for the two different adaptors, BPO-Au (a, b) and BN-Cu (c, d). Not only the inductance (Fig. 4(a) and (c)) but also the ESR (Fig. 4(b) and (d)) vary linearly with the contact resistance. This implies that the variation of inductance and the ESR values is caused due to the R_C during calibration of the inductors, where torque for the tightening of the biding post of the inductor was systematically changed and other measurement conditions were kept unchanged. The real R_S value of the 100 μH standard inductor deduced from the calculated ESR and the R_C values and estimated to be of about 79.23 mΩ which well matches with the certificate value of 80 mΩ provided by the manufacturer as plotted in Fig. 5.

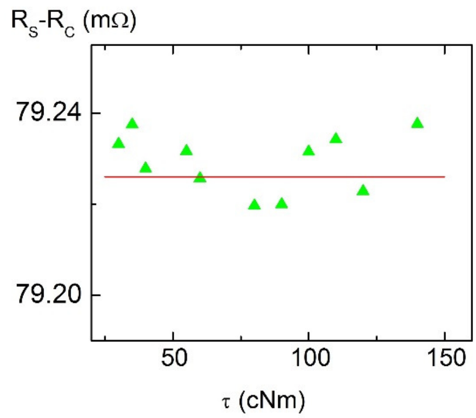

Fig. 5. Estimated equivalent series resistance R_S value. (solid line) indicates the reference value given on the certificate.

The 100 μH standard used in this measurement is equipped with a shorting link on the top panel. The first measurement is made with the shorting link in L position (the coil is connected) and second measurement is made with the shorting link in the L_{OS} position (the coil is dis-connected and the leads are shorted) measuring the internal leads inductance. The certificate value L_{cert} of the standard inductor issued by the PTB which identified as an effective inductance, L_{eff} is obtained from the differences between L and L_{OS}.

To study the effect of the lumped components of the adaptors in the inductance measurement, the L_{ADP}, R_{ADP} and C_{ADP} were measured solely for the adaptors using the same LCR meter. Fig. 6 shows a circuit diagram of the modeled components and the measured values of the lumped components. As shown in Fig. 6, the L_{ADP} of the BN-Cu is considerably larger than that of the BPO-Au but lower C_{ADP} and R_{ADP} values. In fact, the capacitance of the adaptor, C_{ADP} observed acts as stray capacitance and influences the inductance measurements [5].

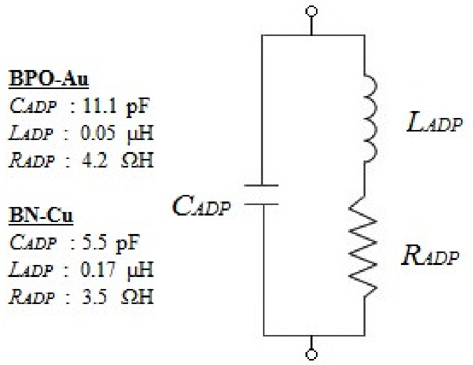

Fig. 6. Measured results and circuit diagram of the lumped components for the adaptor.

The effect of C_{ADP} can be evidenced by the inductance measurement of the adaptor with applied external capacitors, C_{ext} parallel to the C_{ADP}. The inductance of the adaptor measured using the LCR meter increases with increasing C_{ext} value from 0.1 μH to 1 μH. The effects of C_{ext} as a stray factor to L and L_{OS} in measurement of standard inductor are plotted in Fig. 7. The measured effective inductance, L_{eff} using the BPO-Au given a closest reading to the certificate value within the measurement uncertainty.

Hence, the measured impedance $|Z|_{ADP}$ of the adaptor BN-Cu can be calculated from the measured components values (Fig. 6):

$$|Z|_{ADP} = \sqrt{R_{ADP}^{2} + X_{ADP}^{2}}, \qquad (2)$$

where $\overline{Z}=R_{ADP}+jX_{ADP}$ and $X_{ADP}=\sqrt{L_{ADP}^{2}+C_{ADP}^{2}}$. The inductance of the adaptor is defined as:

$$L_{ADP} = \frac{X_{ADP}}{\omega}, \qquad (3)$$

This result shows that the calculated L_{ADP} value of the BN-Cu adaptor is about 0.17 μH which is in good agreement with the large deviation of about 0.2 μH discussed above. This implies that not only the stray capacitance but also the series resistance of the adaptor influenced the inductance measurements of the LCR meter.

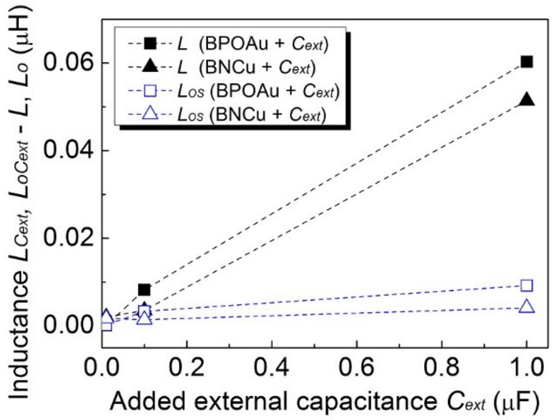

Fig. 7. The addition of external capacitors to determine the stray effects. Dashed lines are linear fitting lines.

Table 1 presents measurement uncertainty budget (relative) for the two different adaptors, BPO-Au and BN-Cu, used for the calibration of the 100 μH standard inductor. The main contributions to the measurement uncertainty are uncertainty of the LCR meter and temperature coefficient of the inductor except for the statistical uncertainty.

The systematic relative uncertainty of the LCR meter taken from the certificate is 55×10^{-6} deduced from the resolution, accuracy and stability of the LCR meter. The temperature coefficient of inductance standard is 30×10^{-6}/°C given by the manufacturer with the temperature variation of the laboratory environmental measurement condition of ±1 °C.

It should be mentioned that the reproducibility of the measured inductance is strongly dependent on the adaptor type. The connection of the BPO-Au adaptor shows much stable contact property than the BN-Cu adaptor where the contact point for fixing banana plugs is not solid and not well defined for every new measurement.

Table 1. Uncertainty budget for the inductance measurements obtained using the 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 inductor	Rectangular B	17	17
Combined un-certainty (k =1)		70	83

IV. NOVELTIES IN THE PAPER

The novelty of this study is to show the importance of making a proper contact at the terminals during the measurement of inductance standards using a suitable adaptor with an optimum force. There are no published results related to the optimum torque needed for a solid contact between adaptor and inductor binding post terminal [6]. Hence, we reported the measurement results of inductance, contact resistance and equivalence series resistance using two types of adapter, BPO-Au and banana with copper (BN-Cu) by systematically applied torque. The measured inductance and the equivalence series resistance obtained using a LCR meter clearly show a linear dependent on the contact resistance caused by the adaptor when applying torque to tighten the binding post of the inductor. Therefore the measured inductance can be corrected by subtraction of the contact resistance contribution calculated through an exponential fitting to the measured data. The results imply that the contact resistance and inductance are dependence on the material type of the adaptors due to the differences in electrical resistivity as well as hardness of the materials when applying torque.

V. CONCLUSIONS

We designed two different types of adaptor, BPO-Au and Banana-Cu, for the inductance measurement using a LCR meter and measured the contact resistance between the adaptor and the 100 μH standard inductor, inductance and quality factor as a function of torque from 25 cN·m to 150 cN·m. All the measured quantities, R_C, L and ESR, are strongly dependent on the adaptor types and torque applied for the tightening of the binding post of the inductor, respectively. The measurement results clearly show that the measured inductance and the ESR value vary linearly with the contact resistance. Therefore, the contribution of the contact resistance caused by the adaptor and torque for the binding post can be corrected from the measured inductance value.

The analysis of the measurement uncertainty and contact resistance measurements shows that the BPO-Au adaptor with low contact resistance and stable contact property is more suitable for the inductance measurement than that of Banana-Cu with relatively large contact resistance and worse contact property of banana plug. The contact resistance between the inductor terminal and the adaptor in inductance measurements is affected by the adaptor material types due to the differences in electrical conductivity as well as hardness of the materials when applying torque.

It is evidenced from the measurement results that the stray capacitance and series resistance of the adaptor significantly influenced the inductance measurement, although the measurements setting of the LCR meter is in an inductance mode “L”.

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VI. ACKNOWLEDGMENT

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