Simple Offset Elimination Technique for Two-Wire Measurements

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Measuring small inductors and capacitors can be challenging with the use of conventional LCR-meters that have a test frequency of 10 kHz or less. With a 10 nH inductor at 10 kHz, the impedance is only 6 mOhms, that is comparable to the resistance of the probes. At a frequency of 100 kHz, the impedance increases to 60 mOhms. On the other hand, a 1 pF capacitor at 10 kHz results in an impedance of 15 MOhms, which makes a capacitive connection between the probes noticeable and affects the measurement of impedance. This paper presents two case studies: an extraction the parasitic inductance of the two-wire probes using the HP4284A LCR-meter and HP16034E test fixture, and extraction of the parasitic capacitance using the LCR-Reader-R2 tweezer-meter. This method enables accurate measurements of sub-nH inductors and sub-pF capacitors using test frequencies below 300 kHz.

Motivation of Work

We develop and manufacture high precision low frequency LCR tweezer-meters such as LCR-Reader-R2 [1] and similar products. They usually use test frequencies of 10 to 100 kHz or lower and this makes measurement of small inductors and capacitors very difficult. We also needed calibrated components in nH range that could be used for calibration of our devices. So, we tried to use the HP5284A bench multimeter to measure small inductors and capacitors, but we ran into serious problems when measuring inductances below 10 nH and capacitances below 1 pF, so we came up with the calibration procedure described below.

Since it was not possible to get larger size components (larger than 1008) with small inductance, we used an alternative approach by making inductors of a piece of copper wire of the required size. For those we used a theoretical inductance estimate as the nominal inductance value.

Impedance Measurement Methods

There are several methods for measuring impedance, each with its own advantages and disadvantages. These methods are described in the literature, such as [2], and can be broadly divided into three groups: current and voltage methods, differential/bridge methods, and resonance methods.

The current and voltage method, also known as the response method, is the most commonly used method. It involves passing a known high-frequency alternating current through the component and measuring the resulting voltage across it. The magnitude of the impedance can then be calculated from the ratio of the voltage and current. The phase angle between the voltage and current can also be measured, and in combination with the impedance, the equivalent capacitance, inductance, and resistance can be determined.

The main advantage of the current and voltage method is that it is a direct method and does not require any reference components. It is also relatively simple to implement and can be used to measure a wide range of impedance values. However, this method is sensitive to parasitic effects such as stray capacitance and inductance in the measurement circuit, which can lead to measurement errors. In addition, it can be difficult to achieve accurate measurements at high frequencies due to the effects of skin effect and proximity effect.

Differential/bridge methods, on the other hand, can provide higher accuracy by compensating for parasitic effects and can be used to measure low impedance values. However, they require the use of reference components, which can add to the complexity of the measurement setup.

Resonance methods are often used to measure inductance values, as they are based on the measurement of the resonant frequency of the inductor connected to a known capacitor. This method is less sensitive to parasitic effects than the current and voltage method, but it can be difficult to achieve accurate measurements at high frequencies.

In summary, each impedance measurement method has its own strengths and weaknesses, and the choice of method depends on the specific requirements of the measurement application.

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We will discuss the most commonly used the current and voltage or response method that is a widely used technique for measuring impedance. It involves passing a known high-frequency alternating current through the component and recording the resulting voltage across it. The magnitude of the impedance can then be calculated from the ratio of these values. Additionally, the phase angle between the voltage and current can be measured, allowing for the determination of the equivalent capacitance or inductance, as well as resistance.

Measurement Procedure

The general idea of the approach is to extract parasitic impedance of the fixture for a specific geometry, namely the distance between the test probes. This impedance obviously is a function of the distance and has to be extracted for every component size. When we measure a set of small components, whether capacitors or inductors, the measured values deviate from the nominal values due to the parasitic offset that can be extracted and used for getting the actual component values.

In order to calibrate our fixture, we needed known small value components with small tolerance which are readily available for smaller size components up to 0603 size. For larger size inductors we mostly relied on hand made single wire inductors which values can be theoretically estimated with a reasonable accuracy.

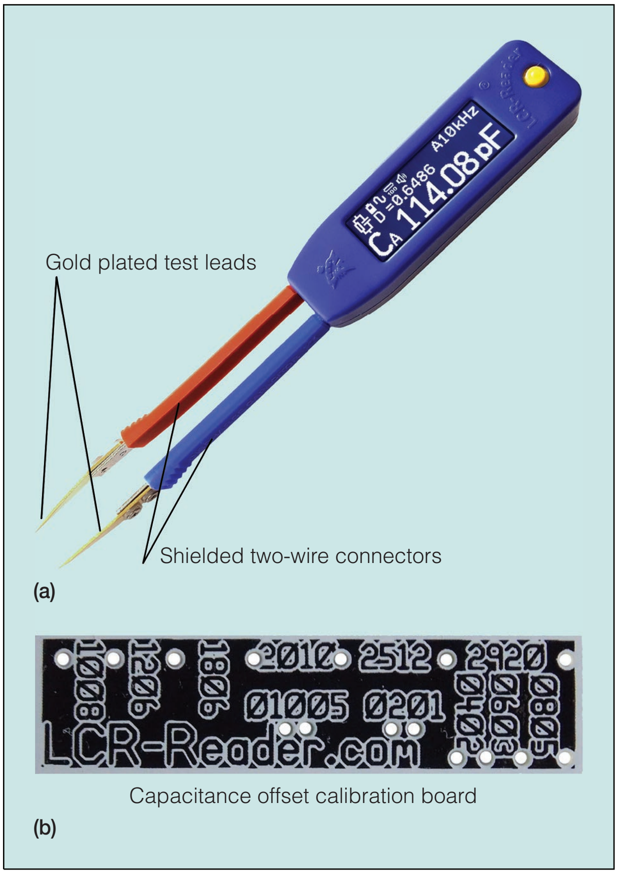

Fig. 1. (a) LCR-Reader-R2. (b) Capacitance offset calibration board.

Open Calibration for Capacitance Measurement

We illustrate this technique using LCR-meter designed and manufactured at Siborg Systems Inc. All measurements were made using the latest model LCR-Reader-R2. The device consists of a set of tweezers with gold plated test leads integrated with a high precision LCR-meter and a display resulting in a lightweight handheld device. The device is shown in Fig. 1 and has shielded two-wire connectors inside each of the tweezer handles ending with the test leads.

The test leads obviously are not shielded and therefore introduce parasitic impedance that has to be eliminated in order to improve accuracy when measuring small value components. This parasitic impedance consists of parasitic capacitance and inductance of the test leads and each of them depends on the distance between the test leads. The parasitic capacitance, often called capacitance offset, results in an additional current path which is noticeable when low current measurements are done, that is high resistance or low capacitance measurements. This parasitic current is proportional to the test frequency and inversely proportional to the distance between the tweezer tips and therefore is especially noticeable when measuring small size and small value capacitors at higher frequencies.

Capacitance Offset Calibration Board

The easiest way to evaluate the capacitance offset would be to use a small dielectric spacer with a proper length between the test leads. What we used in our experiments was a Capacitance Offset Calibration board shown in Fig. 1. The Capacitance Offset Calibration Board provides a reliable method of determining the parasitic offset between the test leads. The dummy PCB uses holes to represent various sizes of components. To use the calibration board, the test leads are placed into the holes corresponding to the size of component under test; and then open calibration is made by pushing the joystick to the right and holding for 2 beeps.

Table 1 presents measurement results made at 100 kHz. A reference Open calibration was made for the component size

Table 1 – Measurement results made at 100 kHz

Size	Length (mm)	C (pF)
01005	0.4	0.249
0201	0.6	0.225
0402	1	0.177
0603	1.5	0.138
0805	2	0.115
1008	2.5	0.098
1206	3	0.077
1806	4.5	0.042
2010	5	0.031
2512	6.3	0.014
2920	7.4	0

set to 2920 (7.4 mm between the tweezer tips). Please note that the results vary slightly depending on the distance between the tweezer handles and surroundings around the test leads. For example, placing a hand near the test leads or applying a stronger pressure to the handles may lead to a few fF change. After open calibration of the device for a specific component size is properly made, the component value may be measured with absolute accuracy of about 3 fF.

Capacitance Measurement Results

As an illustration we made measurements of extremely small capacitors of 0.1 to 10 pF. High tolerance components were used with the tolerance about 0.01 to 0.05 pF or about 2%. All measurements presented in Fig. 2 fit well into the tolerance ranges indicated by error bars on the pictures. If no proper offset calibration was done, the error could easily exceed 0.1 pF or 50% to 100% of the capacitance value for smaller capacitors.

Short Calibration for Inductance Measurement

Whereas the parasitic capacitance of the probes decreases with increasing distance between the probes it is the other way around for parasitic inductance. The reason for it is very simple, imagine a very small component with a single wire connected on both sides. Since the currents in the wires are flowing in opposite directions, magnetic fields of each of them are almost fully mutually compensated and the resulting parasitic inductance is nearly zero. This is exactly why twisted pair connection is very popular in communication systems. When we separate the wires, the compensation becomes smaller and thus resulting magnetic field and hence the parasitic inductance increases.

In contrast to capacitance offset extraction, when the use of a spacer does not noticeably affect the parasitic capacitance, for inductance offset we have to use a piece of conductor between the test leads in order to create the short for inductance offset extraction. Such a conductor is going to create an additional inductance which has to be taken into account when evaluating the offset. So unfortunately, there is no easy way of getting the parasitic inductance the same way the capacitance offset was extracted as was described above. Therefore, a new method was suggested using linear regression analysis of the measurement data.

Inductance Offset Extraction Using SMD Components

Smaller inductors require 100 MHz to 1 GHz or even higher test frequency that may not be readily available. Typically inexpensive handheld LCR- meters use 10 kHz whereas more advanced meters, such as LCR-Reader [1] may offer 100 and 250 kHz test frequency. Much more expensive bench type LCR meters may offer 1 MHz and higher test frequency but at a much higher cost.

Use of lower test frequencies entails the following issues:

- Much higher measurement accuracy is needed because lower impedance values have to be possible to measure
- Therefore, a much more accurate extraction of the probe parasitic inductance is required
- Since manufacturers provide datasheets measured at much higher frequencies, lower test frequency leads to an overestimation of the inductance value, with deviation exceeding 10%, e.g., [3].

Six different component sizes: 01005, 0201, 0402, 0603, 0805 and 1008 were used in experiments with inductance values from 0.3 to 100 nH. A few test frequencies were used for comparison of the results, namely 100, 250 and 1,000 kHz. A series of measurements have been performed and linear regression analysis was utilized to extract the parasitic inductance of the test fixture for each component size.

In order to extract the parasitic inductance of a test fixture, using an inductor with a known inductance is an ideal approach. However, in reality, inductors are manufactured with some tolerance which results in deviation between components with the same nominal value. Hence, we utilized the

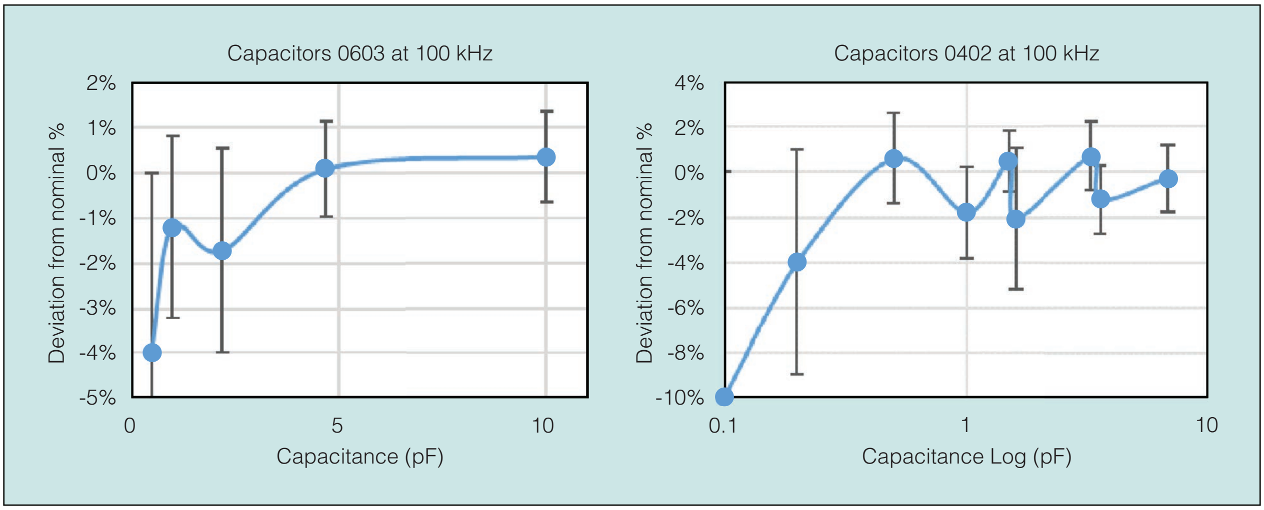

Fig. 2. Deviation of measured capacitance values from the nominal values.

Table 2 – Tested components and extracted parameters

Component	**01005**	**0201**	**0402**	**0603**	**0805**	**1008**
Tolerance	0.1 – 0.3 nH	0.1 – 0.3 nH 5%	0.1 – 0.3 nH 5%	0.1 – 0.3 nH 5%	0.3 nH 5%	0.3 nH 5%
Test Frequency	500 MHz	100, 500 MHz	100 MHz	100 MHz	100 MHz	100 MHz
Manufacturer	Murata, Sunlord	Wurth	TDK, Taiyo	Wurth	Eaton, Abracon	TDK
L_{offset} Component	0.45	0.636	0.923	1.075	1.661	3.242
α	1.137	1.208	1.136	1.139	1.062	1.0063
L_{offset} Wire	–	–	0.785	0.888	0.877	1.011

average deviation obtained by linear regression analysis as the parasitic inductance of the test fixture.

To account for the correction to the actual inductance value due to low frequency, we used the following expression to extract the actual inductance from the measured value:

$$L_{measured} = \alpha\, L_{actual} + L_{offset} \qquad (1)$$

The expression for extracting the actual inductance from the measured value takes into account a correction factor due to low test frequency. The symbols used in the expression have obvious meanings. The coefficient α in the expression reflects this correction factor and depends on the component type, manufacturer technology, and test frequency used by the manufacturer for their data sheet measurements. To extract both the coefficient α and the parasitic inductance offset L_{offset}, linear regression analysis is performed on the measurement data for a number of components for each of the 6 different sizes.

We make the assumption that the measured inductance is proportional to the actual (measured at high frequency) inductance value, and in order to limit the effect of larger tolerances for larger inductors on the accuracy of extracted parameters, we restricted our measurements to smaller inductors. The values of the coefficients α and L_{offset} were extracted using linear regression analysis of measurement data for each of the 6 different sizes, and are presented in Table 2. To extract the actual inductance values for higher test frequencies, we use equation (1) along with linear regression analysis.

Inductance Offset Extraction Using Single Wire Inductors

Larger size low value inductors (below 10nH) are not available and therefore we used made in house single wire inductors instead. They were made of 0.65 mm copper wire. Our very limited capabilities allowed to achieve 0.05 mm length accuracy. For inductors with lengths larger than 1 mm, that is 0402 component size equivalent, this accuracy level (under 5%) was acceptable. By subtracting the theoretical value of a linear wire inductance calculated according to [4] from the value measured using HP4284A LCR-meter we extracted the inductance offset of the fixture. The values obtained for L_{offset} for single wire inductors are presented in Table 2.

The experiments used various components, mainly multilayer chip inductors from manufacturers such as Wurth Elektronik, TDK, Taiyo Yuden, Murata, Eaton, and Abracon. The extracted inductance offsets for both methods are compared in Fig. 3, and they are similar for component sizes 0402 and 0603. However, the difference between the two methods increases significantly for sizes 0805 and especially 1008.

A possible reason of the significant difference of the extracted L_{offset} is a contribution of the inductor pads that are significantly bigger for larger component sizes and therefore affect the geometry of the fixture. This discrepancy in the extracted inductance offsets for larger component sizes may also be attributed to the fact that smaller inductors with this size are not available. As inductance values increase, the component tolerance also increases, especially for 0805 components, which typically have a tolerance of 5%, resulting in a tolerance of 1 nH. For 1008 components, the tolerance leads to a typical tolerance of 2 nH. As a result, the effect of component value fluctuation and the absence of lower inductance value components when using regression analysis may lead to an

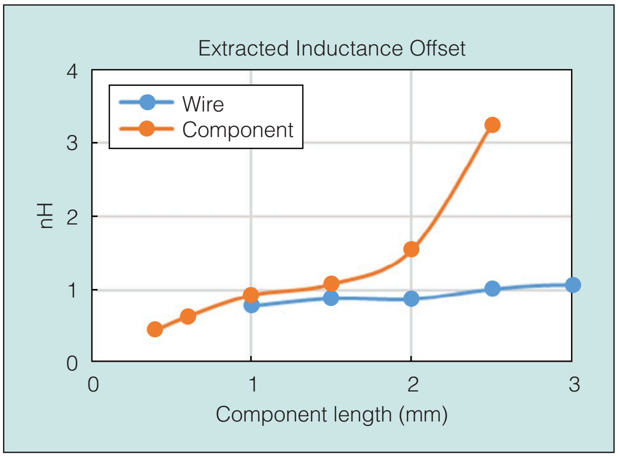

Fig. 3. Extracted inductance offset for the two methods of L_{offset} extraction: using SMD inductors and single wire inductors, from [5] (© IEEE 2022, used with permission).

overestimated offset inductance. This minor deviation in the offset values for larger size components does not have a significant impact on the relative accuracy because these components typically have much higher inductance values.

Inductance Measurement Results

The results in Fig. 4 demonstrate that taking into account the parasitic inductance and low frequency correction can lead to rather accurate measurements of inductance. The corrected values are all within the tolerance of the components, while non-corrected values show considerable deviation. The error bars in the figure represent component tolerances, which vary from 0.1 nH to 0.3 nH for smaller inductors and 5% for larger ones. The typical deviation due to the lower test frequency is about 10–20%, which is not identifiable for inductors under 1 nH but becomes clearly visible for inductors of 10 nH and higher. For inductors under 10 nH, the main contribution to the deviation comes from the offset inductance L_{offset}, whereas at higher inductance values, the frequency correction factor becomes dominant.

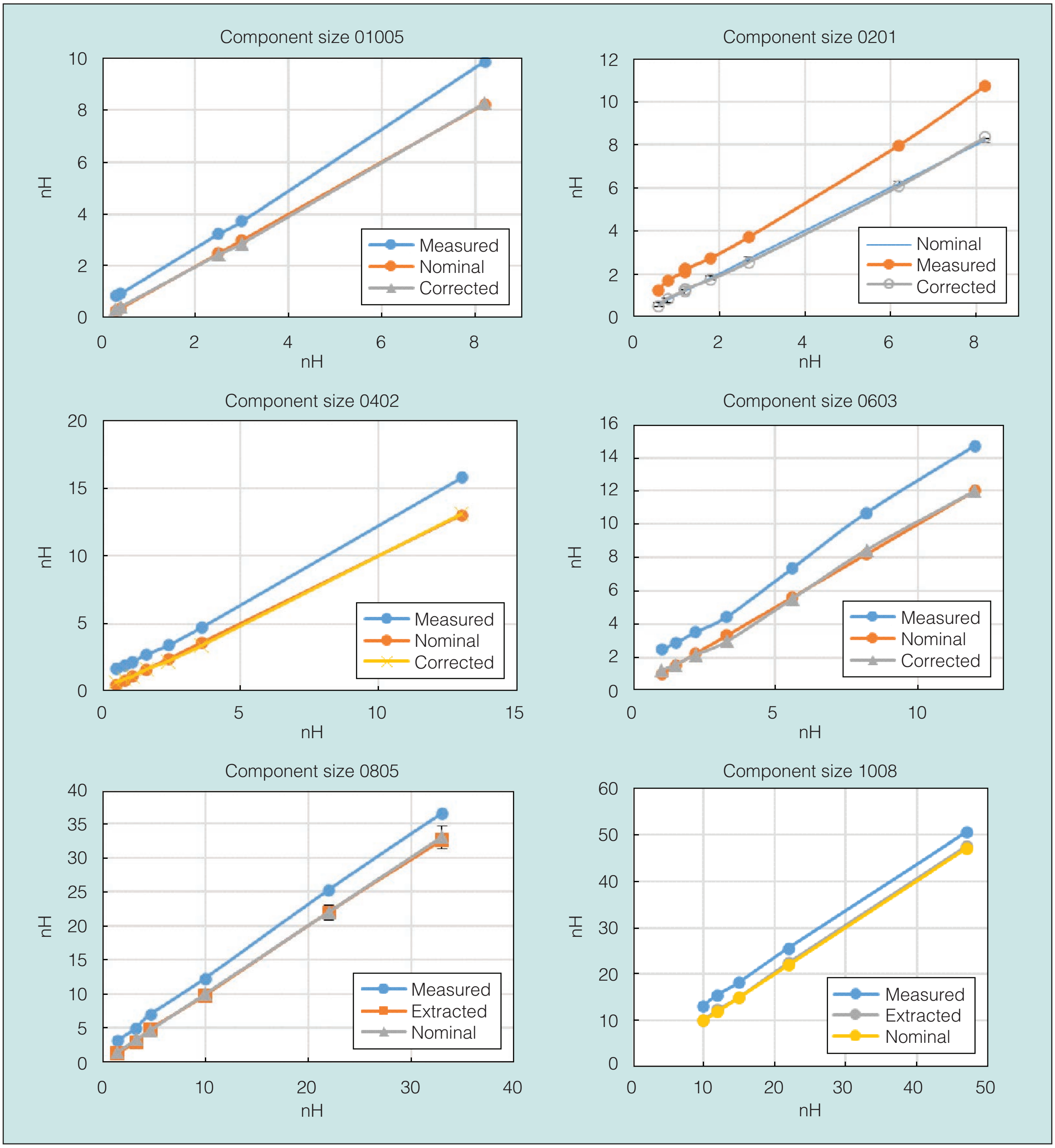

Fig. 4. Measurement results for small inductors using HP4284A at 1 Mhz test frequency, from [5] (© IEEE 2022, used with permission).

The results of the measurements are displayed in Fig. 4 for inductors of 01005, 0201, 0402, 0603, 0805, and 1008 sizes, which were tested using HP4284A at 1 MHz frequency. The measurement results, nominal inductance values, and corrected values obtained using equation (1) are shown. The figure indicates that for small inductance values, the measured values deviate considerably from the nominal values, exceeding the component tolerance range by over 100%. The extent of deviation varies with the component size, which is expected since the test fixture's geometry, particularly the distance between the probes, is adjusted for each size. This deviation is due to the parasitic inductance of the test fixture.

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