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## Note: Rapid offset reduction of impedance bridges taking into account instrumental damping and phase shifting

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The sensitivity of an imperfectly balanced impedance bridge is limited by the remaining offset voltage. Here, we present a procedure for offset reduction in impedance measurements using a lock-in amplifier, by applying a complex compensating voltage external to the bridge. This procedure takes into account instrumental damping and phase shifting, which generally occur at the high end of the operational frequency range. Measurements demonstrate that the output of the circuit rapidly converges to the instrumentally limited noise at any frequency.   2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4795554>]

Automatically balanced impedance bridges are used in a wide range of measurements, for instance, capacitive sensors,<sup>1</sup> measurements of conduction phenomena,<sup>2</sup> magnetic susceptibility measurements on, for instance, high temperature superconductors,<sup>3,4</sup> and dielectric spectroscopy.<sup>5</sup> Automatic iterative procedures are well known in digital control systems.<sup>6,7</sup> There are several bridge balancing procedures<sup>8–10</sup> that automatically optimize a component inside the bridge to reduce any offset voltage, in order to measure at the highest sensitivity possible.

Alternatively, the offset can be reduced externally to the bridge<sup>11,12</sup> by applying a compensating voltage, which is subtracted from the voltage of the bridge using a differential amplifier. This compensating voltage is independent of components in the bridge and it can be determined by an automatic and iterative “nullification” procedure, such that it nullifies the output of the circuit, which is measured by a lock-in amplifier. However, near the maximum frequency of the bandwidth of the lock-in amplifier, the measured remnant signal is affected by instrumental damping and phase shift, which can severely slow down the nullification process.

In this note, we report on an improved nullification procedure, which takes into account any frequency dependent damping and phase shifting of the compensating voltage itself. Consecutively, we describe in this note the experimental setups that were used as a test case, our nullification procedure and the test results of our method.

The circuit used to demonstrate our nullification procedure is presented in Fig. 1. It is remarked that this is merely an example, since the nullification procedure is independent of the type of circuit used. The sketched bridge circuit is used to perform dielectric spectroscopy on a sample present between the electrodes of a capacitor. High sensitivity is required to measure small changes in capacitance as a function of frequency. The other capacitor acts as reference capacitor.

The circuit consists of two synchronized sinusoidal oscillators (OSC 1 and 2), a differential pre-amplifier (AMP), and a differential lock-in amplifier (LIA). OSC 1 applies a voltage over the bridge and OSC 2 applies the compensating voltage  $V_{\text{comp}}$ , which is subtracted from the amplified voltage  $V_{A-B}$  by the LIA.

The differential amplifier (AMP) rejects the common mode signal of the bridge points *a* and *b* (see Fig. 1). Due to practical limitations, the reference capacitor does not exactly match the sample capacitor (without sample), resulting in a background signal (the offset) which limits the sensitivity. This offset is nullified by  $V_{\text{comp}}$ , which is determined using the nullification procedure on an empty sample capacitor. Then, the sample can be measured at the highest sensitivity, by applying the same  $V_{\text{comp}}$  on a filled capacitor.

The non-zero output  $V_{\text{diff}}$  of the imperfectly balanced bridge circuit was nullified using two sets of hardware: (1) two Signal Recovery 7280 digital lock-in amplifiers (maximum frequency 2 MHz) in combination with a Yokogawa FG120 dual channel function generator (maximum frequency 2 MHz) and two 10  $\Omega$  resistors and (2) a Zurich Instruments HF2LI lock-in amplifier (specified maximum frequency of 50 MHz, but operating up to 100 MHz) in combination with two Zurich Instruments HF2CA dual channel pre-amplifiers. The latter setup is slightly different from the former setup: the two capacitors are directly connected to a dual channel pre-amplifier (in single-ended input mode with selectable resistor of  $10^1 - 10^6 \Omega$ ) to measure  $V_A$  and  $V_B$  separately, which are then connected to the second pre-amplifier to measure  $V_{A-B}$ . The hardware is controlled by a personal computer using National Instruments LABVIEW software. More detailed diagrams of both setups are provided as the supplementary material.<sup>13</sup>

To nullify the bridge circuit, a compensating voltage  $V_{\text{comp}}$  is applied. First, the background signal  $V_{A-B}$  is measured directly without compensating voltage, starting with the least sensitive range of the LIA, and switching successively to more sensitive ranges if no overload is expected.<sup>12</sup> Then, a compensating voltage  $V_{\text{comp}}$  is applied, which is set equal to the measured background signal  $V_{A-B}$ , and the remnant signal

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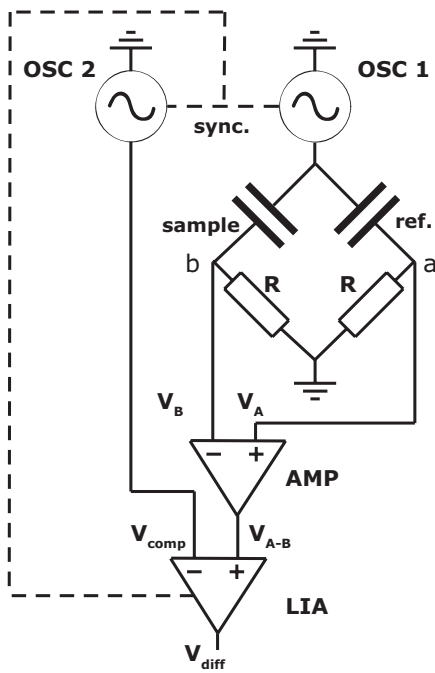


FIG. 1. Schematic diagram of a differential impedance bridge with offset reduction.

$V_{diff}$  is measured. Finally, since  $V_{diff}$  is not necessarily zero,  $V_{comp}$  is adjusted by an iterative procedure as discussed below, to further reduce  $V_{diff}$ .

In a previously reported procedure,<sup>12</sup>  $V_{comp}$  was adjusted for each iteration by increasing it by the remnant  $V_{diff}$  of the previous iteration. In the  $n$ th iteration step of this nullification

procedure,  $V_{comp}$  is thus determined by

$$\text{Procedure I : } V_{comp}^{n+1} = V_{comp}^n + V_{diff}^n, \quad (1)$$

where all voltages are complex.

Our improved nullification procedure accounts for damping and/or phase shifting of  $V_{comp}$ . To do so, it is assumed in this model that the set  $V_{comp}$  is first multiplied by a *complex constant*  $\tilde{\alpha}$  before it is subtracted from  $V_{A-B}$ . In absence of any damping or phase shifting, this constant is equal to 1. Hence, the minimized signal  $V_{diff}$  is determined by

$$V_{diff}^n = V_{A-B} - \tilde{\alpha}^n V_{comp}^n. \quad (2)$$

After the initializing step in which  $V_{comp}^0 = V_{A-B}$ , the constant  $\tilde{\alpha}$  can be calculated from the previous iteration by  $\tilde{\alpha}^n = (V_{A-B} - V_{diff}^n) / V_{comp}^n$ . The damping and phase shifting could depend on the compensating voltage itself, hence  $\tilde{\alpha}$  needs to be determined for each iteration. In our nullification procedure,  $V_{comp}$  is then determined by

$$\text{Procedure II : } V_{comp}^{n+1} = \frac{V_{A-B}}{\tilde{\alpha}^n} = \frac{V_{comp}^n}{1 - V_{diff}^n / V_{A-B}}, \quad (3)$$

where again all voltages are complex.

Convergence is considered to be reached, when the remnant signal  $|V_{diff}|$  does not decrease any further after a certain number of iterations and the procedure is terminated.

The improved nullification procedure II (Eq. (3)) was tested and compared to procedure I (Eq. (1)). The magnitude of the remnant signal  $|V_{diff}|$  was recorded during a sequence of 10 iterative steps at different measurement frequencies, for both procedures and both sets of hardware (Fig. 2). At the highest frequencies, the difference between both procedures

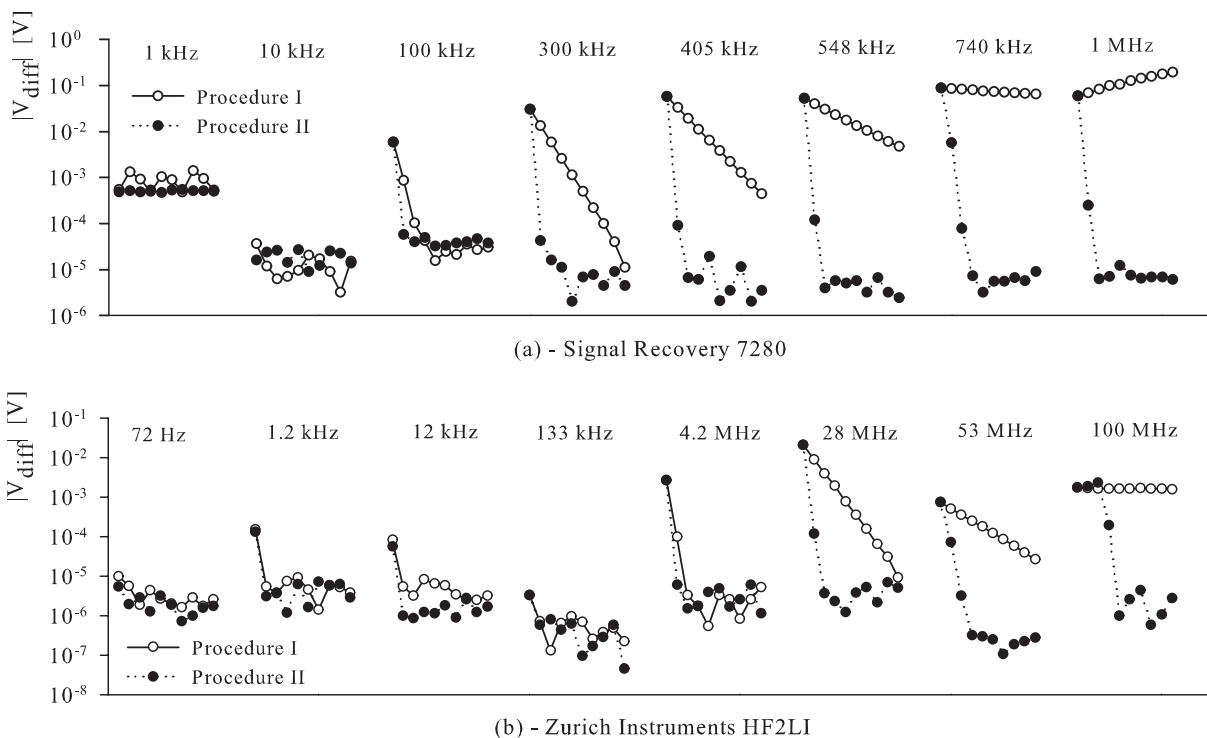


FIG. 2. Nullification of the remnant signal  $|V_{diff}|$  in 10 iterations with procedure I (○) and II (●), at several frequencies; using (a) Signal Recovery 7280 and (b) Zurich Instruments HF2LI lock-in amplifiers.

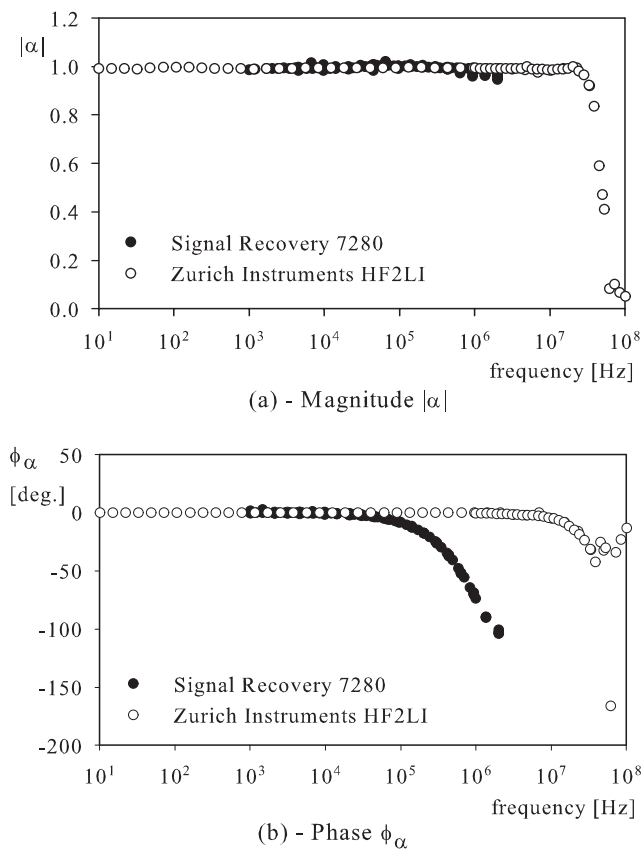


FIG. 3. The magnitude  $|\tilde{\alpha}|$  (a) and phase  $\phi_{\tilde{\alpha}}$  (in degrees) (b) of the complex constant  $\tilde{\alpha}$ , using Signal Recovery 7280 (●) and Zurich Instruments HF2LI (○) lock-in amplifiers.

is striking. Whereas procedure II converges within 3–5 iterations, procedure I does not converge to the noise level within 10 iterations or does not converge at all. At the lowest frequencies, both procedures converge fast and reach the noise level within 2–3 iterations, so that procedure II has no great advantage over procedure I at these frequencies. Depending on the measurement resistance  $R_s$ , the setups have a white noise plateau of 7 to 70 nV/ $\sqrt{\text{Hz}}$ , and below 10 kHz the Zurich Instruments setup reveals  $f^{-1}$  noise.<sup>14</sup>

The slowness or absence of convergence of procedure I at the highest frequencies correlates with an  $\tilde{\alpha}$  deviating from 1, whose magnitude and phase are plotted in Fig. 3. As the

frequency approaches the specified maximum frequency of the bandwidth of the hardware, both hardware setups show an decreasing magnitude and increasing phase lag of  $\tilde{\alpha}$  near the  $-3$  dB level. Nullification procedure II accounts for these deviations and rapidly converges to the optimal  $V_{\text{comp}}$  at any frequency. If  $\tilde{\alpha}$  is known in advance as a function of frequency for a particular setup, it could be used in the first guess of the compensating voltage ( $V_{\text{diff}}^0 = V_{A-B}/\tilde{\alpha}$ ), in order to reach an even faster convergence. Our tests with two different hardware setups show that the improvement realized by this method offers a larger operational frequency range through better offset reduction, irrespective of the type of hardware used.

The described nullification procedure can be directly used as an improvement on impedance bridges where a complex offset reduction is a time-consuming step. Even if damping or phase shifting of the compensating voltage occurs, this procedure rapidly converges within a few iterations, whereas the previous procedure converges very slowly or does not converge at all.

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