A Low-Frequency Current Comparator
For Precision Resistance Measurements

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\textbf{ABSTRACT} — Two prototypes of a current comparator for operation at low frequencies in the 0.1 Hz to 1 Hz range and at room temperature have been realized. Experimental tests include the determination of the frequency-dependent sensitivity and a comparative measurement of the ratio of two standard resistors with nominal values of 1 kΩ and 100 Ω. The realized current comparator is the main ratio standard in a precision ac resistance bridge operated without need of liquid helium which will be one of the main measurement instruments for a future graphene-based quantum Hall resistance standard.

\textbf{Index Terms} — Resistance measurement, CCC, low frequency, measurement uncertainty, sensitivity, current comparator.

\section{I. INTRODUCTION}
Resistive metrology comprises two essential tasks, the calibration of standard resistors with decade nominal values against the quantum Hall resistance and the comparisons within an ensemble of decade nominal resistors. The highest accuracy is achieved with the measurement bridges including a current comparator as a main precision ratio device. The most common (and even commercialized) realizations of this scaling device are the cryogenic current comparator (CCC) \cite{1-2} and the direct current comparator (DCC) \cite{3-5}. The CCC with a SQUID as the magnetic field null-detector can be considered to be ultimately precise, i.e., the ratio error can be kept negligibly small by appropriate design. However, operation of a CCC is rather complicated and requires low temperature. Different from that, the DCC is a room-temperature device, which is easier to handle, but the accuracy is limited. An alternative to both is the low-frequency current comparator (LFCC) working with sinusoidal signals at frequencies of about 1 Hz \cite{6}, combining easy handling, robustness and room-temperature operation with precision in the parts-in-10\textsuperscript{9} level. Dc resistance measurement using a CCC or DCC can be done at arbitrarily low frequency and practically is performed with current reversals at a frequency of order 10\textsuperscript{3} to 10\textsuperscript{4} Hz. In contrast to these instruments, the LFCC cannot measure the resistance ratio at dc and consequently, its application requires calibration, i.e., determination of the ac-dc correction. Even so, this is not compromising the overall performance of the device as the on-site comparisons using BIPM’s transportable setup \cite{7} are based on a combination of CCC and LFCC since many years. More specifically, thanks to the stability of calibrated low-frequency current comparator ratios, the LFCC is an appropriate travelling transfer standard. Nowadays, an increased interest in such a robust, cheap and easy-to-operate resistance calibration device arises from the prospective availability of a graphene-based standard of resistance. A combination of both could serve as the fundament of practical resistance metrology without any need of liquid helium. In this contribution we present preliminary studies on LFCCs exploring the frequency range from 1 Hz down to 0.1 Hz.

\section{II. THE LOW-FREQUENCY CURRENT COMPARATOR}

In an LFCC, windings of two different roles are wound on the same high-permeability toroidal core: 1) a certain number of ratio windings and 2) a detection winding. The LFCC is completed by electrostatic and magnetic shields (Cu foil and two annealed µ-metal cans). The detection coil represents the inductive component of a parallel LC circuit. The alternating currents to be compared have the frequency of this circuit’s resonance. These currents with amplitudes $I_1$ or $I_2$ will flow through ratio windings with numbers of turns $N_1$ or $N_2$, respectively. The detector’s sensitivity is then defined as the ratio of the ac voltage in the resonant circuit and the input signal $N_2 \cdot I_2$ generated in any of the ratio windings. For our study, we have built two LFCCs with inductances of the detection coils of order 10\textsuperscript{8} H. The lower-inductance version, LFCC-A, has a detection coil of about 2500 turns and a magnetic core of relative permeability about 2.5 $\times$10\textsuperscript{2}, whereas for LFCC-B, the higher-inductance version, the corresponding numbers are about 3000 and 1 $\times$10\textsuperscript{3}. The capacitance in the LC circuit can be selected out of five values ranging from 28 µF to 700 µF. When combined with LFCC-A or LFCC-B, the resulting resonant frequencies are in the range from 0.1 Hz to 1.1 Hz by design. The use of a resonant detector implies a decrease of sensitivity with decreasing frequency and also a significant influence of the LC circuit’s quality factor. Note, that earlier realizations of the LFCC \cite{6} concept did not allow for operation at frequencies significantly lower than 1 Hz. But, the possibility to perform LFCC-based resistance comparison at several frequencies of about 1 Hz and below is highly valuable for the intended determination of the ac-dc correction. The overall numbers of turns in the ratio windings are 400 and 2560 for LFCC-A or LFCC-B, respectively.
III. EXPERIMENTAL RESULTS

At first, we have determined the ten resonant frequencies (for two detection coil inductance and five capacitance values) and the corresponding sensitivities at the resonant peak. This has been done using an SRS 850 lock-in amplifier. A 0.4 nA current was biased from the output of this device through a 10 MΩ resistor into 100- or 512-turns ratio windings of LFCC-A or LFCC-B, respectively. Before being connected to the input of the lock-in, the ac voltage across the detection coil has been pre-amplified by 10^3 using an ultra-low noise chopper amplifier [8]. The results are summarized in Fig. 1. The resonant frequency covers the range from 1.02 Hz (LFCC-A and 28 µF) down to 0.144 Hz (LFCC-B and 700 µF), for the quality factors we found values from 25 to 12.

![Fig. 1. Resonant-frequency dependent sensitivity of both LFCC prototypes.](image)

In a next step, LFCC-A has been integrated into the 1 Hz bridge setup of BIPM and used for a test of a 10 : 1 ratio comparison choosing the ratio windings of 200 and 20 turns. Even in the rather provisional configuration without appropriate thermal stabilization of the resistors with the nominal values 1 kΩ and 100 Ω, the measurement results agree better than within 1 part in 10^8 with those obtained with the CCC bridge of PTB as shown in Fig. 2. Note, that these preliminary results do not include a separately determined ac-dc correction for the values from the LFCC measurements, i.e., the discrepancy between the LFCC and CCC results is a measure for the LFCC’s ratio error.

VI. CONCLUSION

Two prototypes of current comparators for operation in the 0.1 Hz to 1 Hz frequency range – a notable expansion towards lower frequencies – were fabricated and tested. The appreciably high sensitivity of the comparators has been achieved amongst others by using state-of-the-art high-permeability magnetic cores. The developed LFCC could replace the CCC in commercial bridges if the software and control electronics are appropriately modified. This would reduce the expenses on liquid helium and simplify the calibration of resistors.

![Fig. 2. Results of a series of 1 kΩ to 100 Ω ratio measurements using LFCC-A operated with BIPM’s ac bridge electronics at 1 Hz and the dc CCC bridge of PTB. In both cases a voltage of 0.17 V has been applied. The errors bars represent the standard type-A uncertainty.](image)

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REFERENCES