Calibration setup for ultralow-current transresistance amplifiers

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Abstract—We describe a calibration setup for the transresistance of low-current amplifiers, based on the capacitance-charging method. The calibration can be performed in the current range of typical interest for electron counting experiments. The setup implementation is simple and rugged, and is suitable to be embedded in larger experiments where the amplifier is employed. The calibration is traceable to units of capacitance and of time. The base relative accuracy of the implementation is in the 10⁻⁷ range.

I. INTRODUCTION

In the future revision of the International System of Units (SI) [1] the unit of electrical current, the ampere, will be redefined in terms of the elementary charge e. The value of e, presently 1.602 176 620 8(98)×10⁻¹⁹ [2], will be defined as exact (that is, with zero uncertainty). Electron counting experiments [3]–[5] will allow the practical realization of the ampere [6]. The currents generated in these experiments are typically below 1 nA range, and thus must be amplified by large factors (10⁶ to 10⁷) to be exploited for metrology purposes. The amplification can be performed either with large-ratio cryogenic current comparators [7], [8], or with dedicated current amplifiers [9], [10]. During the development of the experiments, ultralow-current transresistance amplifiers [11]–[13] are commonly employed. The typical transresistance gain R ranges from 10³ Ω to several 10⁶ Ω. A traceable gain calibration of these amplifiers allows to verify the fundamental relation \( I = nef \), where \( I \) is the current generated from single electron devices, \( f \) the electron counting frequency, and \( n \) is the integer number of electrons counted for each cycle (\( n \) ranges from 1 to 3).

In the following, we describe a calibration setup for the transresistance gain of ultralow-current amplifiers based on the capacitance-charging method [14]–[21]. The method allows to produce accurate dc currents in the range 100 pA to 100 nA and is insensitive to non-idealities of the input stage of current amplifiers, such as voltage burden and finite input resistance. Currents can be generated with typical relative uncertainties in the 10⁻⁴ range [14]–[16]; the performances of different measurement setups based on the method have been verified in an international intercomparison [22].

The setup here proposed allows to perform a calibration of the transresistance gain \( R \) of a current amplifier traceable to the capacitance of a gas-dielectric capacitor \( C \), and the period \( T \) of a low-frequency timebase. The setup configuration is simple and compact, and it is possible to embed the entire setup within the main electron counting experiments, and thus achieve quasi-line calibrations of \( R \).

An example of calibration of a specific amplifier model (FEMTO mod. DDPCA-300), popular in electron counting experimental setups [11]–[13] and other nanophysics experiments [23]–[25], is given. For this amplifier, the setup allows to calibrate the nominal transresistance gain of 100 GΩ with a relative uncertainty of about 30 × 10⁻⁶.

II. PRINCIPLE OF OPERATION

The operating principle of the calibration setup is shown in Fig. 1. Voltage \( v_{in}(t) \) is applied to a differentiating capacitor to generate the test current \( i(t) \)

\[
i(t) = \frac{C}{dt} \frac{dv_{in}(t)}{dt} \tag{1}
\]

The amplifier \( A \), of which the transresistance gain \( R \) has to be calibrated, generates an output voltage \( v_{out}(t) = Ri(t) \), hence the relation

\[
R^{-1} = C \frac{1}{v_{out}(t)} \frac{dv_{in}(t)}{dt} \tag{2}
\]

holds. Equation (2) shows that the traceability of the measurement of \( R \) is given by \( C \), a timebase, and a...
Fig. 2. Schematic diagram of the calibration setup, see Sec. III-A for a description. A pictorial representation of the waveforms of $v_{\text{in}}(t)$ and $v_{\text{out}}(t)$ is also shown.

IEEE-488 bus

Fig. 3. A photo of the calibration setup corresponding to the schematic diagram of Fig. 2. G is on the bottom left; C and A in the center; $v_{\text{in}}$ on top left; $V_{\text{out}}$ on the right. A detail of C and A is given in Fig. 4.

Fig. 4. Detail of setup, showing the direct connection (no cable) of the injection capacitor $C$ (on the left) to the transresistance amplifier $A$ (center of the picture) to minimize currents related to the dielectric absorption in the connection insulators.

by the voltmeters $V_{\text{in}}$ and $V_{\text{out}}$, synchronized since they share the same trigger signal $T$. The samples of $v_{\text{in}}(t)$ and $v_{\text{out}}(t)$ are acquired with an interface bus (IEEE-488) for off-line processing.

As shown in Fig. 3, the whole circuit is wired by coaxial leads. To reduce possible effects of dielectric absorption, $C$ and $A$ are connected directly, without any cable, as can be seen in Fig. 4.

The waveform shape of $v_{\text{in}}(t)$ generated by G has a symmetric trapezoidal shape, with a very long period, as can be seen in Fig. 5. This specific shape has three different slopes: positive, negative and zero; these slopes correspond to three different nominal calibration current values $+I_{\text{nom}}$, $-I_{\text{nom}}$ and $I = \pm 0$. The test current $I = \pm 0$ allows to determine the offset of $A$ in the course of the measurement.

B. Instruments employed

1) Ramp generator: G is a purposely-built voltage source. The generated signal $v_{\text{in}}(t)$ has a maximum span of $\pm 10V$, and the ramp sections of the trapezoidal waveform have a slope of $\approx \pm 0.1V \text{ s}^{-1}$ (adjustable). The positive and negative voltage ramp phases have a duration of $\approx 200s$ each; the phases of constant voltage also have a duration of $\approx 200s$. Hence, the total period of one $v_{\text{in}}(t)$ cycle is $\approx 800s$. The source is based on analog electronics; it is battery-powered and free-running (thus requiring no control signal), in order to achieve complete galvanic isolation and help to reduce the interferences in the calibration circuit. The source output is generated by an analog pure integrator, which is driven by a three-state (positive, zero, negative) constant current source of adjustable amplitude. The loss in the integrating dielectric capacitor are compensated with an active feedback network, which is manually adjusted in order to achieve the maximum linearity of the voltage ramps. A more complete...
TABLE I
INJECTION CAPACITORS EMPLOYED IN THE CALIBRATION SETUP
LISTED BY NOMINAL CAPACITANCE \( C_{\text{nom}} \).

| \( C_{\text{nom}} \) | Model                      |
|----------------|---------------------------|
| 1pF           | General Radio mod. 1403-K  |
| 10pF          | Sullivan mod. C80001      |
| 100pF         | Sullivan mod. C80002      |
| 1000pF        | General Radio mod. 1404-A |

description of the source is given in Ref. [16].

2) Injection capacitor: \( C \) has to be a gas-dielectric (or vacuum) capacitance standard, because all solid-dielectric capacitors show the phenomenon of dielectric absorption [27], which give deviations from Eq. 1. For the current range investigated, commercial standard capacitors having nominal values \( C_{\text{nom}} \) in the range 1pF to 1000pF are adequate. The specific models employed are listed in Table I. The capacitors have been modified to employ low-dielectric-absorption connectors (Teflon insulation); for the same reason, the solid-dielectric trimming capacitors have been removed.

The value of \( C \) is measured as a two terminal-pair standard [28, Ch. 2] with a commercial capacitance bridge (Andeen-Hagerling mod. 2500A) at the frequency of 1kHz. The calibration is traceable to the Italian national standard of electrical capacitance.

3) Voltmeters: \( V_{\text{in}} \) is an Agilent mod. 3458A multimeter, which acquisition is in dc sampling mode, with the autozero and autorange functions disabled. \( V_{\text{out}} \) is an Agilent mod. 34401A multimeter, also configured for dc sampling. Both these voltometers are in external trigger mode, and are synchronously triggered by a precision timer \( T \), at the sampling frequency of \( \approx 950\text{MHz} \). All samples are acquired via the IEEE-488 bus and offline processed. Although not required by the proposed method (see discussion in Sec. II), the voltmeters are routinely calibrated, with traceability to the Italian national standard of dc voltage.

C. The device under test

The calibration setup has been tested with a FEMTO mod. DDPCA-300 transresistance amplifier A. The amplifier has a nominal transresistance range \( R_{\text{nom}} \) manually switchable from 10kΩ to 10TΩ and is specified to be stable for capacitance at the input up to 10nF, therefore for all capacitance standards of Tab. I. The voltage output span is \( \pm 10V \); the current noise is dependent on \( R_{\text{nom}} \) and reaches \( 200\text{pA Hz}^{-\frac{1}{2}} \) in the highest gain ranges. The specified accuracy of \( R_{\text{nom}} \) is \( \pm 1\% \) with a temperature coefficient of \( 3 \times 10^{-4} \text{K}^{-1} \). The amplifier has a configurable output lowpass filter; all measurements reported have been performed in the so-called full bandwidth (dc to 400Hz) mode.

Fig. 5. The outcome of a typical measurement \( (R_{\text{nom}} = 10 \text{GΩ}, C_{\text{nom}} = 1 \text{nF}, I_{\text{nom}} = 95 \text{pA}) \). Red line (—) is the trapezoidal ramp signal \( v_{\text{in}}(t) \); blue line (—) is the test current \( i(t) \). The sign of \( i(t) \) is determined by the sign of the slope of \( v_{\text{in}}(t) \); when \( v_{\text{in}}(t) \) is constant, \( i(t) = 0 \).

Fig. 6. Time sequence of the amplifier equivalent error the input \( \Delta i(t) \) (see Sec. IV for the definition). The four different dot colors correspond to the four different phases of \( v_{\text{in}}(t) \), • corresponds to \( v_{\text{in}} \) positive ramp slope, and to \( i(t) = +I_{\text{nom}} \). • negative ramp slope, \( i(t) = -I_{\text{nom}} \). \( v_{\text{in}}(t) \) constant positive, \( i(t) = +0 \). \( v_{\text{in}}(t) \) constant negative, \( i(t) = -0 \). The offset of A is computed from the average of the \( i(t) = +0 \) and \( i(t) = -0 \) phases.

IV. RESULTS

A. Description of the measurement

The setup has been employed to calibrate the transresistance nominal settings \( R_{\text{nom}} = 10\text{GΩ}, 100\text{GΩ}, 1\text{TΩ} \) and \( 10\text{TΩ} \) of A. All measurements have been performed in a shielded and thermostated (23.0(5)°C) room. Each calibration has been achieved by running the system for about 50 cycles of \( v_{\text{in}}(t) \), corresponding to a total measurement time of 10h. The calibration strategy and
For the nominal transresistances in Tab. II together with the corresponding uncertainty (see Sec. IV-C). For the nominal transresistances of the amplifier are reported in Tab. II corresponding to the average of the $\delta R$ point values over the whole measurement cycles.

### B. Calibration summary

The calibrated values of $\delta R$ for different test currents and nominal transresistances of the amplifier are reported in Tab. II together with the corresponding uncertainty (see Sec. IV-C). For the nominal transresistances $R_{\text{nom}} = 1\, \text{T} \Omega$, $10\, \text{M} \Omega$ and $10\, \text{T} \Omega$ the calibration is performed with two different test currents. For $R_{\text{nom}} = 1\, \text{T} \Omega$ significant differences among the $\delta R$ values obtained with different current magnitudes and sign; these discrepancies deserve further investigation.

#### C. Traceability and uncertainty

As explained in Sec. II, the traceability of the calibration is provided by the calibrated value of the injection capacitor $C$ and the period of timebase $T$. Several other effects contribute the measurement uncertainty. Among them we list the measurement noise, possible frequency dependencies of $C$ (which is measured at 1kHz but employed at mHz frequency in the setup), current leakages in $C$, tracking and nonlinearities of $V_{\text{in}}$ and $V_{\text{out}}$. These influence quantities are under investigation and therefore the uncertainties reported in Tab. II should be considered preliminary and not including the in-use uncertainty (that will account for time and environmental drifts).

### V. Conclusions and outlook

The proposed setup can calibrate the transresistance gain of amplifier suitable for the measurement of ultralow-valued dc currents. The uncertainty achieved is one or two order of magnitudes better than the corresponding manufacturer specifications. The calibration uncertainties reported is still preliminary, however the calibration accuracy is one-two orders of magnitude better than the typical manufacturer accuracy specifications. A complete uncertainty budget will be reported at the Conference.

The method is simple and can be embedded in an electron-counting experiment with relative ease. As Eq. 2 shows, the method requires traceability to capacitance and time units, since it involves only voltage ratios: this opens the possibility of further simplification in the measurement setup, by performing voltage ratio measurements with a single, two-channel sampling instrument which would not require absolute voltage calibration. This
alternative setup is presently under investigation, and will be reported at the Conference.

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