An Ultra-Low Current Meter for Aerosol Detection

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ABSTRACT

An ultra-low current meter (ULCM) is used for charged aerosol measurement. In this work, a prototype of the ULCM was designed, built and experimentally tested. Commercially-available operational amplifiers were used to construct the meter. The range of the current measurement of the ULCM was from 1 to 500 pA, corresponding to number concentrations of aerosol particles in the range of 10^{11} - 10^{14} particles/m^3. The ULCM was relatively simple, inexpensive and compact. The ULCM's performance was evaluated with a high-impedance current source and compared with a commercial electrometer, Keithley model 6517A. It was found to be in accord with theoretical predictions and close agreements with the commercial instrument. The prototype meter was proven to be promising for aerosol detection.

Key words: Aerosol, Electrometer, Low current, Prototyping

INTRODUCTION

Airborne particles have significant effects on human health and the Earth's climate because they have a relatively long residence time in the atmosphere and are able to penetrate deep into human lung. Measurement and classification of airborne particles' size have become an important issue. For this purpose, aerosol-size analyzers based on electrical mobility determination were developed to measure size distribution in sub-micrometer range (Intra, 2006). For most electrical mobility analyzers (EMA), an aerosol detector in the form of an ultra-low current meter (ULCM) is required to sense the presence of these particles. The ULCM is normally employed to measure the exceedingly small amount of electrical current associated with the charged particles collected on an electrode ring of the sizing instruments. If the aerosol charge distribution is known accurately in terms of the number of electrical charges per particle and the fraction of particles which are charged as a function of particle size, it is possible to determine both the size of the particles being measured as well as the total number concentration of the particles. The electrical current variations encountered in the electrical mobility analyzers are several orders of magnitude, the range of several nA down to pA and fractions of fA. Commercially-available ULCMs are generally found in most EMAs (Graskow, 2001; Kulon et al., 2001; Intra and Tippayawong, 2006a, 2006b), but they are expensive. There have been numerous studies and developments on the ULCM. Barthwal et al. (1981) developed an electrometer preamplifier for measurement of DC voltage, current and resistance in high-resistivity materials. The range of measurement for voltage, current and resistance are from 30 μV to 10 V, 10^{-2} to 10^{-13} A and 10^{3} to 10^{13} Ω, respectively. Yao and Yoon (2000) designed a low-noise electrometer, capable of measuring current at the femtoampere level. The low-noise electrometer has amplification of 0.1 V per 1 pA. Harrison and Aplin (2000), Aplin and Harrison (2000, 2001) developed a computer-controlled electrometer, capable of either high-impedance voltage measurements or fA current measurements for use with the Gerdien ion counter. Measured currents were reported to be typically about 100 fA. Rajput (2003) introduced monolithic linear current electrometers for high-frequency current measurements. It is capable of measuring the input current from 100 pA to 1.0 mA and has a bandwidth in excess of 30 MHz. It is evident that most ULCMs are different in terms of specific applications, construction, cost, measurement range as well as resolution.

In this study, an inexpensive and yet sensitive ULCM is developed, suitable for detection of high-concentration aerosols such as those from combustion source. A prototype of the ULCM was designed and constructed. The performance of the ULCM was evaluated with a high-impedance current source and compared with a commercial ULCM (Keithley model 6517A). The transient calculation of the ULCM circuit was also performed by the PSIM software package.

BACKGROUND THEORY

The signal current, I_p, from the deposition of charged particles on each electrode ring of the EMA is given by:

$$I_p = n(d_p)eQ_aN_p \tag{1}$$

where $n(d_p)$ is the average number of elementary charges carried by particles with diameter d_p, e is the value of the elementary charge, Q_a is the sample aerosol flow rate, and N_p is the aerosol number concentration. The signal current measured at each electrode ring was then evaluated for the number concentration of the aerosol particle being measured. Thus, the aerosol number concentration of particles is related to signal current as follows:

$$N_p = \frac{I_p}{n(d_p)eQ_a} \tag{2}$$

The range of particle number concentrations that can be measured with the EMA is mainly determined by the sensitivity of the ULCM. As a rough estimate at the worstpredicted conditions, Equation 2 suggests that signal current levels in the range of 1 pA per 10^{11} particles/m^3 will be produced. In this study, particle number concentrations from combustion are usually much higher than 10^{11} particles/m^3, therefore the ULCM with 1 pA resolution should be sufficient for this application.

SYSTEM CIRCUIT DESCRIPTION

The schematic presentation of the ULCM circuit design for aerosol detection of the EMA is shown in Figure 1. This circuit is a simple current-to-voltage converter, where the voltage drop caused by a current flowing through a resistor is measured. The circuit adopted two cascaded negative feedback amplifiers. Extra component in this circuit is primarily for fine offset voltage adjustment and input/output protection. A±12V power supply capable of providing 100 mA is required. The feedback capacitor and RC low-pass filter were used to reduce high-frequency noise and to prevent oscillations of the amplifier output (Yao and Yoon, 2000; Rajput, 2003). In order to avoid expensive construction, commercially-available low-cost monolithic operational amplifiers were used. The commercially-available operational amplifiers used in this circuit is the Burr-Brown OPA128LM, which was designed for low current measurement and featured ultra-low input bias current (> 75 fA maximum) and low-induced input noise (> 4 µV peak-to-peak) (Burr-Brown Corporation, 1995). The output voltage, V_o, of this circuit is given by the following equation:

$$V_o = G_1 G_2 V_i \tag{3}$$

where:

$$G_1 = \frac{R_{f1}}{R_{i1}}, \;\; G_2 = \frac{R_{f2}}{R_{i2}} \tag{4}$$

$$V_i = I_i R_{i1} \tag{5}$$

G_1 and G_2 are the gain of the first and second amplifiers. R_{f1} and R_{f2} are the feedback resistors of the first and second amplifiers. R_{i1} and R_{i2} are the input resistors of the first and second amplifiers, respectively. V_i is the input voltage of the circuit and I_i is the input current of the circuit. Substituting Equations 4 and 5 into Equation 3, the output voltage of the circuit is given as:

$$V_o = I_i \frac{R_{f1} R_{f2}}{R_{i2}} \tag{6}$$

This circuit gives an output voltage of 10 mV per 1 pA of input signal current. For readout purposes, the output voltage of the ULCM circuit was connected to a unipolar 12-bit analog to digital converter (ADC), controlled by I^2C bus from the external personal computer via parallel port interface. The digital ADC signal was processed by computer software, based on Microsoft Visual Basic programming.

While the design of the ULCM circuit was relatively simple, the construction of the circuits was somewhat less straightforward. Care was taken to shield the AC input to the power supply, and to route these wires away from the ULCM circuit input (Oliver, 1976; Barthwal et al., 1981). Because of the extremely-low current levels being measured, standard circuit fabrication techniques were not satisfactory. The reason for this was that stray leakage currents between the circuit power supply and the ULCM inputs through the printed circuit board material itself were more than sufficient to overwhelm the measured input currents. In addition, the presence of any oils or other contaminants from fingerprints or anti-static treatment chemicals may provide conductive path with lower resistance than the intended circuit paths. To avoid leakage problems, the amplifier inputs were all isolated from the printed circuit board. Connection pins were held against the electrometer ring, using Teflon standoffs. Connections between these pins and the amplifier inputs were made in the air above the circuit board. Contamination was minimized first by cautious fabrication techniques, and secondly, by thorough cleaning of the assembled circuit with ultrasonic bath, followed by rinsing in isopropyl alcohol after fabrication. Further references on low-current circuit fabrication techniques can be found in Burr-Brown Corporation (1995) and Pease (1991, 1993).

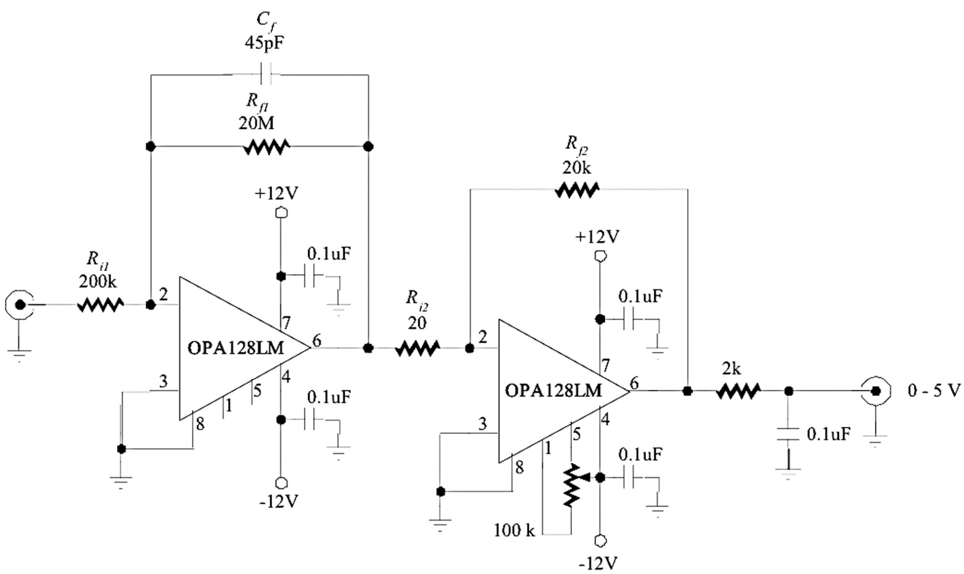

Figure 1. Schematic presentation of the prototype ULCM circuit design.

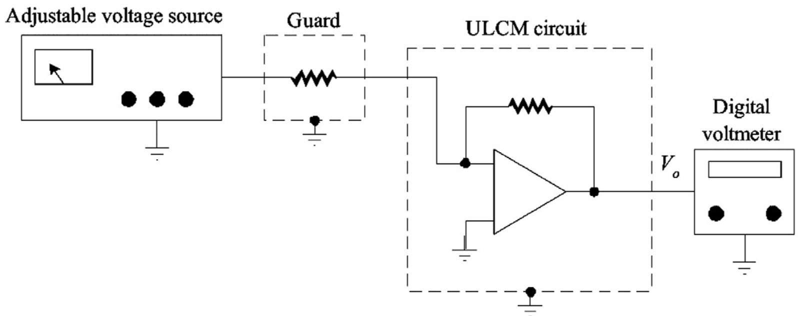

Figure 2. Schematic presentation of the experimental setup for the prototype ULCM test.

EXPERIMENTAL SETUP

Figure 2 shows the experimental setup used to evaluate the fabricated ULCM circuit performance. In this study, the ULCM circuit was calibrated with a current injection circuit, high-impedance current source (Harrison and Aplin, 2000; Aplin and Harrison, 2000, 2001). This circuit consists of an appropriately high-standard resistor (10 GΩ) and an adjustable voltage source in the range between 0–5 V. The output current of this circuit can simply be calculated from the Ohm's law. The range of the output current is from 1 pA to 500 pA. It should be noted that the ULCM circuit input was operated at virtual ground potential during calibration and subsequent current measurement. The output voltage from the ULCM circuit was measured and recorded by a highly-accurate digital voltmeter. The voltage reading was then translated into the current measurement via Equation 6.

RESULTS AND DISCUSSION

Figure 3 shows the transient calculation of the ULCM circuit, carried out using the PSIM, a simulation software package specifically designed for power electronics and motor control which was developed by Powersim Inc. The transient times were varied from 0–10 ms. It was found that steady state of the output voltage from the circuit could be reached in about 6 ms. Figure 4 provides comparison of measured current from this work and a commercial ULCM (Keithley model 6517A) with high-accuracy current source. Difference in measured values between the two instruments is given in Table 1. The data covered the range between 0–500 pA. Generally, the currents measured from this work were found to agree well with those measured by the Keithley model 6517A. Very small difference was obtained at the high end of current measurement. Towards the low end, the relative magnitude of the two current readings was observed to be increasingly different. It is worthy to point out that there were some interferences on the connector at small potentials. Additionally, leakage of currents through the body of the connector can potentially impair the performance of the ULCM significantly. Detailed investigation of this problem may be undertaken in the future study to determine how large the effect is.

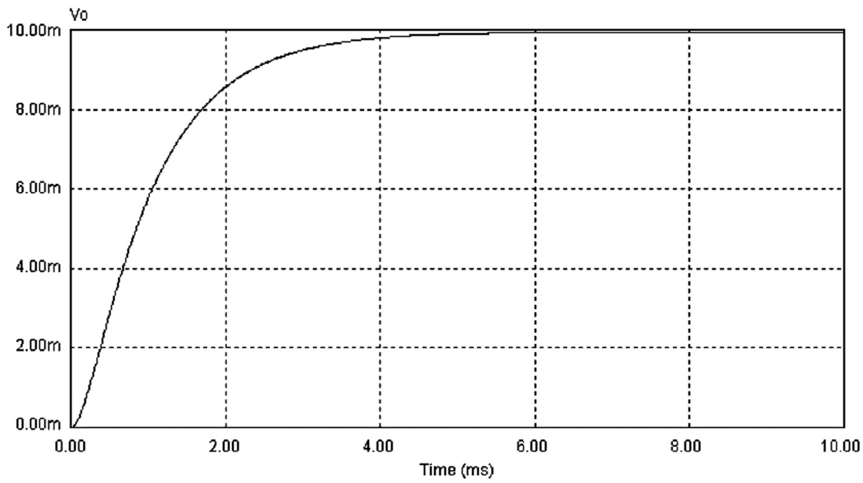

Figure 3. Transient calculation of the prototype ULCM circuit determined by PSIM.

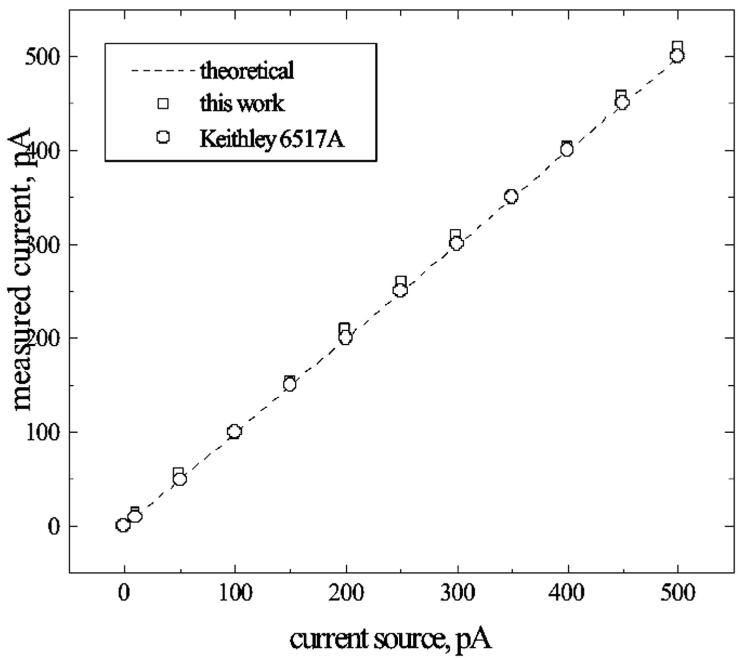

Figure 4. Performance comparison between the prototype and commercial ULCMs.

Table 1. Current measurement comparison.

Theoretical prediction (pA)	Keithley 6517A (pA)	This work (pA)	Difference
0	0.22	0.67	-0.46
10	9.95	14.17	-4.22
50	49.79	56.32	-6.53
100	100.00	98.00	2.00
150	150.25	154.31	-4.06
200	200.41	209.39	-8.99
250	250.55	260.01	-9.46
300	300.84	309.07	-8.24
350	350.74	351.24	-0.50
400	400.93	403.97	-3.04
450	451.07	458.13	-7.06
500	501.22	510.06	-8.84

CONCLUSION

The ultra-low current meter has been presented and described in this paper. It was able to measure current in the range of 1 pA to 500 pA, corresponding to the number concentration of particles in the range of 10^{11} - 10^{14} particles/m^3. The prototype ULCM has been constructed and calibrated against high-impedance current source. Within the test conditions considered, it was demonstrated to have comparable performance to the commercial instrument. These promising results show that the developed ULCM prototype may be used successfully in aerosol detection.

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