Compensation of Voltage Measurement Based on Smart Phone

Liqun Xu[1], Jia Liu [2], Caxia Lv[1], Wenlang Nui [3]

[1]College of Information Technology, Beijing Union University, Beijing,100101,China
College of Information Technology , Key Laboratory of Information Service Engineering, Beijing Union University
[2]*School of Computer Science and Engineering* , Beihang University, Beijing,100101,China
[3]College of Applied Science and Technology, Beijing Union University, Beijing,100107,China

***Abstract* — A compensation method is addressed for voltage measurement with smart phone. Analysis of measurement system and measurement results shown that the system parameters and ADC are main reasons causing measurement error. In additional, the discussion about the system shows that measurement error is unavoidable but could be reduced with some compensation methodology. From the analysis and discussions, this paper proposed a compensation method based on the control and calculation with smart phone and called average parameter compensation method (APC). With APC the error could be reduced effectively.**

Keywords - voltage measurement ; compensation method ; smart phone

I. INTRODUCTION

Smart phone has a strong computation ability [1][2] [3] and could be a processing kernel of some terminals of measurement and/or Internet of Things (IoT) [4][5] [6][7][8].

To use the data process function there should be voltage signals input interface. There are three way can be used for signals acquisition, the USB, the blue tooth, and audio channel. The USB and Blue tooth are data transfer channels; they can transfer data in full-duplex. And the audio channel is the headset port and also a full-duplex [5].

To be used as a measurement tool a circuit for voltage signal acquisition is needed which is connected with a smart phone through USB, Blue tooth, or headset port. The acquisition circuit is a module with deferent architectures [4][5][7]. In general there are two kind of architecture, Analog Test Module (ATM, composed of signal adapter and harvest energy circuit) and Digital Test Module (DTM, composed of signal adapter, ADC, digital interface circuit, and harvest energy circuit). ATM could only be connected with smart phone through headset port and use the ADC of the audio path of the smart phone. The DTM could be connected with the smart phone through USB, Blue tooth, and/or headset port. There is the error in the measurement result ether ATM or DTM path, and the error could be corrected by some computation algorithm executed in smart phone.

General there are measurement errors caused by analog circuitry and ADC. The measurement result could not be used for signal reconstruction if the error large enough. The ATM and DTM are used for low frequency and amplitude voltage signal acquisition with a smart phone in this paper. It is hoped that measurement results could be compensated with some calculation to reduce the effect of measurement errors.

An error compensation method is addressed in this paper. The method could correct most part of the error based on calibrating test. The experience shows that the method is useful for test system with smart phone.

In this paper, part 2 the system architecture and signal channel were discussed; part 3 shows the characteristics of measurement result and the errors; part 4 discussed errors characters; and Part 5 presented a compensation method and discussed compensation; effect.

II. SYSTEM ARCHITECTURE AND SIGNAL CHANNEL

A. *System Architecture*

The headset of a Smart phone could be used as a signal channel [3] [4] [5]. To use this channel to transfer signal into a smart phone, a special circuit is needed. Such special circuit and APP software together can form a useful portable signal acquisition terminal [4] [5].

A measurement system architecture with smart phone is shown as Fig.(1).

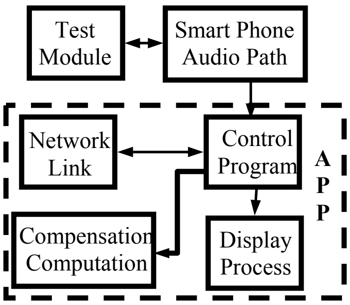

Fig.1 System Architecture

In Fig.1, Test Module (TM) is a circuit module for voltage measurement which can harvest energy from a single channel of the smart phone and is controlled by the APP software. There is a special function module to process the data obtained from TM to increase measurement accuracy in the APP and it is called "Compensation Computation". The APP can control the TM get into self-test state to get some correcting parameters used for compensation computation.

B. Signal Channel

A circuit for signal acquisition terminal is shown as Fig.(2),

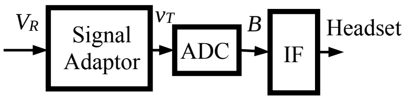

Fig.2 Special circuit for smart phone

In Fig.2, Signal Adaptor is a circuit module includes amplitude grade circuitry and anti-aliasing filter, and IF. IF module is the interface module constructed with digital Modem, UART, and harvest energy circuit. Since frequency and amplitude limitation of the channel, the amplitude and frequency of the signal V_R must be under 0~0.2V and 1 kHz respectively [4] [5].

Suppose system transfer function of Signal Adaptor is K_0, and the highest frequency of input signal is less than a half frequency of the transfer function (lower than 1 kHz). In such situation the ADC output data is

$$B = \left[\frac{v_T}{\Delta}\right]_2 \tag{1}$$

Where Δ is the resolution ratio of the ADC with N bit,

$$\Delta = \frac{V_{REF}}{\sum_{i=0}^{N-1} 2^i} = \frac{V_{REF}}{2^N - 1} \tag{2}$$

V_{REF} is reference voltage of ADC.

The Signal Adaptor module is used for signal processing to match the limitation of the headset channel of a smart phone. The circuit block diagram is shown as Fig.(3).

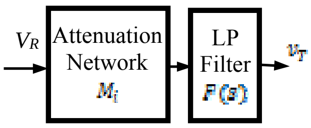

Fig.3 Signal Adaptor module

Suppose M_i is a constant determined by grading circuit (for example the attenuation network) as shown in Fig.3, $F(s)$ is a low pass (LP) filter for anti-aliasing. The module transfer function is

$$K_0 = M_i F(s) \tag{3}$$

Suppose that the signal frequency band is lower than a half of cutoff frequency of the LP filter, $F(s)$ could be considered as a constant. Let $s = 0$,

$$F(s) = \frac{A}{1 + s\tau} = A = F(0)$$

and so

$$K_0 = M_i F(0) = M_i A \tag{4}$$

Considering the offset v_K of the Adaptor the module output is

$$v_T = K_0 V_R + v_K \tag{5}$$

v_T is the input signal voltage of the ADC.

III. ANALYSIS OF MEASUREMENT

A. Measurement result

Let the true voltage for measurement is $V_R \geq 0$, expected value of adaptor transfer function and output offset are $K_0 \geq 0$ and $v_K > 0$, respectively, the ADC input signal could be written as following

$$v_T = K_0 V_R + v_K \geq 0 \tag{6}$$

Expression (3) shows that K_0 is a system parameter determined by circuitries of the adapter so there is a difference between expected value and actual value. Suppose $K = K_0(1 + a)$ where K_0 is expected value of system design and $|a| \geq 0$ is the deviation caused by circuitries. a and V_K are unknown and unequal for each adapter. So the input signal of the ADC is

$$v_T = KV_R + v_K \geq 0 \tag{7}$$

The acquisition result of V_T could be formed with ADC result

$$V_T = B\Delta \tag{8}$$

Where B is ADC output and

$$B = \left[\frac{v_T}{\Delta}\right]_2 \tag{9}$$

Measurement result can be obtained with expression (7) and (8).

In general from works of ADC that $v_T \geq V_T$ and the biggest deviation is Δ. And from works of ADC,

$$\Delta \geq v_T - V_T = KV_R + v_K - B\Delta \geq 0 \tag{10}$$

This means that the unrecoverable error from the ADC is determined by expression (2).

Expression (10) shows the error from ADC only and $V_T = B\Delta$ is not value of system input signal voltage V_R. The V_R has to be reconstructed from $V_T = B\Delta$.

Expression (7) shows

$$V_R = \frac{v_T - v_K}{K} \tag{11}$$

This means that to get true value V_R is imposable due to expression (10).

Let V_{Rt} is measurement result calculated with expression (7) and (8). Measurement result will reconstructed by some calculation.

From expression (8) a calculation result $V_{Rt} = V_{Rt0}$ is

$$V_{Rt0} = \frac{B\Delta}{K_0} \quad (12)$$

From expression (7) a calculation result $V_{Rt} = V_{Rt0}$ could be

$$V_{Rt0} = \frac{B\Delta - v_K}{K} \quad (13)$$

Ignoring a and v_K expression (12) gives a simple result without any compensation. Considering the influence of a and v_K Expression (13) gives a compensated measurement result.

B. Reasons of causing measurement error

Reasons of causing measurement error include effect of signal adaptor for signal voltage, disturbing of K_0, quantization error of ADC, and so on.

a) Effect of signal adaptor. To according with circuit analysis, the signal adaptor is a load of the circuit being measured because there is an input resistance of the adaptor and can influence the voltage of testing point on the circuit being measured if the input resistance is not greater than the output resistance of the circuit being measured.

b) Parameters changing of the adaptor. The adaptor is an analog circuit and its transfer function decided by the circuit parameters such as passive elements value, gain of amplifiers, and so on. The error of transfer function is exist because the circuit elements cannot be the designed value exactly. The error could influence measurement result as shown as expression (5).

c) Error from ADC. There is a quantify error for all ADC. Therefore the true value of measured signal voltage could not be reconstructed exactly.

To the module shown as Fig.(2). the frequency of measured signal is very lower than cutoff frequency of the adaptor, and also input resistance of the adaptor is very high comparing with output resistance of measured circuits, therefore, the main reason of effect error could be transfer function and ADC.

From discussion above the measurement error of V_R is unavoidable but could be reduced with some compensation methodology.

IV. ANALYSIS OF MEASUREMENT ERROR

A. Measurement error

Let absolute error is

$$\varepsilon_a = |V_R - V_{Rt}| \quad (14)$$

Relative error for the measurement, in this paper, is defined as following

$$\delta = \frac{|V_R - V_{Rt}|}{V_R} = \frac{\varepsilon_a}{V_R} \quad (15)$$

Considering expression (10)

$$\Delta \geq |K_0 V_R \delta + a V_R + v_K| \quad (16)$$

From expression (12) and (13), and consider $K = K_0(1+a)$

$$\begin{cases} \delta_0 = \dfrac{|KV_R - B\Delta(1+a)|}{KV_R} = \dfrac{|v_T - V_T - (v_K + aV_T)|}{KV_R} \\ \varepsilon_{a0} = \left|V_R - \dfrac{B\Delta(1+a)}{K}\right| \end{cases} \quad (17)$$

And

$$\begin{cases} \delta_c = \dfrac{|KV_R - B\Delta + v_K|}{KV_R} = \dfrac{|v_T - V_T|}{KV_R} \leq \dfrac{\Delta}{KV_R} \\ \varepsilon_{ac} = \left|V_R - \dfrac{V_T - v_K}{K}\right| \end{cases} \quad (18)$$

Let $K_0 = 1$, $a = 0.1$, $V_{REF} = 2$V, N=8, $v_K = 0.1V_{REF}/(2^N - 1)$, Fig.4 shows relative error δ_0 and δ_c. It is very clear that $\delta_0 \gg \delta_c$ in some voltage interval.

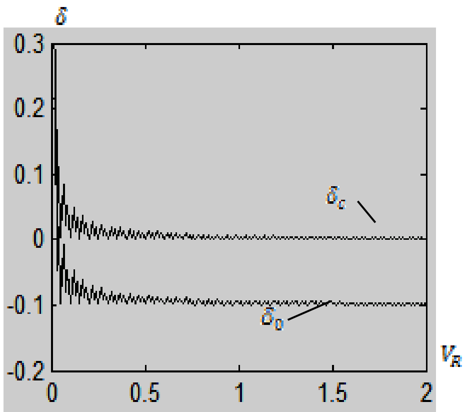

Fig.4 δ_0 and δ_c

Expression (16), (17) and (18) show that Quantization error of ADC is a fixed error and could not be removed;

Relative error δ could be reduced if ε_a and/or v_K is removed; and the fewer ε_a and v_K the less δ.

B. Relative error when $0 \leq V_R \leq 0.1V_{REF}$

Fig.4 shows that relative error is larg when V_{REF} and Δ are determined.

Consider expression (18)

$$\delta_c \leq \frac{\Delta}{KV_R} \quad (19)$$

This means

$$\delta_c KV_R \leq \Delta \quad (20)$$

where δ_c=0.1~0.3.

To meet expression (20)

$$KV_R \leq \frac{\Delta}{0.1 \sim 0.3} \approx \frac{2}{255}(10 \sim 3.3) = 0.078931 \sim 0.025588 \quad (21)$$

Expression (21) shows that if $KV_R < 10\Delta$, relative δ_c will

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be large.

V. COMPENSATION METHOD

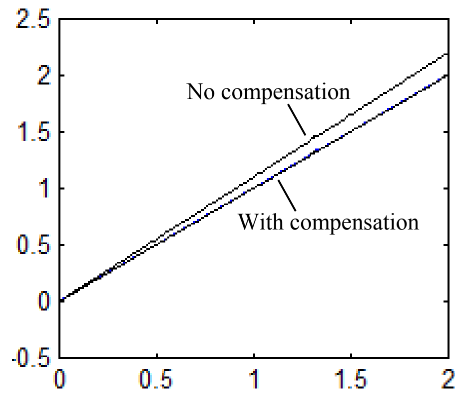
A. *Compensation method*

From part 4 the measurement result could be calculated with expression (13)

$$V_{Rto} = \frac{D\Delta - v_K}{K} \qquad (13)$$

To the system shown as Fig.2 a and v_K could be consider as constant. This means that a and v_K could be determined after the system produced and kept in APP as application data.

Let $K_0 = 1$, $a = 0.1$, $V_{REF} = 2$ V, $N =$ 8, $v_K = 0.1V_{REF}/(2^N - 1)$, Fig. 5 shows measurement result with compensation and without compensation.



Fi.g.5 Measurement result

It should be noted that Fig.(5) shows the absolute error is very small even though the relative error is large with expression (21).

B. *a and v_K*

How to get a and v_K is the key of compensation method given by 5.1. An average testing method is used in this paper.

In the case of $v_K > \Delta$, let $V_R = 0$ is the input of the adapter and average of multi testing result $\bar{B}_0$, from expression (7)

$$\bar{v}_K = \bar{B}_0\Delta \qquad (22)$$

Expression (22) is the v_K used in expression (13).

It has to be noticed that to get $\bar{v}_K$ is difficult in general because $v_K < \Delta$. The $v_K \approx 1$ mV so the v_K was ignored in this paper.

Next let k is a known value such as 0.8 or 1 and the voltage at input point of ADC is

$$V_R = V_{R0} = kV_{REF} \qquad (23)$$

Within a period of time, such as 1 ms, converting V_{R0} several times, such as M times, and calculate the average directly

$$\bar{V}_{R0} = \frac{1}{M}\sum_{i=0}^{M-1} V_{R0i} = kV_{REF} \qquad (24)$$

Let the V_{R0} in expression (23) is the input signal of the adaptor shown as Fig. 2. Therefore the input signal voltage at the input point of the ADC is

$$v_T = K\bar{V}_{R0} + \bar{v}_K = KkV_{REF} + \bar{v}_K \qquad (25)$$

The converting result is B_0 .

Within a period of time, such as 1 ms, converting v_T several times, such as M times, and calculate the average directly

$$\bar{B}_0 = \frac{1}{M}\sum_{i=0}^{M-1} B_{0i} \qquad (26)$$

Consider $K = K_0(1+\alpha)$, the average $\bar{V}_{R0}$ and $\bar{B}$,

$$K\bar{V}_{R0} = K_0(1+\alpha)\bar{V}_{R0} = \bar{B}\Delta - \bar{v}_K \qquad (27)$$

Therefore

$$K = \frac{\bar{B}_0\Delta - \bar{v}_K}{\bar{V}_{R0}} \quad or \quad a = \frac{\bar{B}_0\Delta - \bar{v}_K}{K_0\bar{V}_{R0}} - 1 \qquad (28)$$

In this paper $V_{R0} = 0.8V_{REF}$.

Let K=1.01, N=8, a=0.01, $v_K = (0 \sim 0.2)\Delta$, $V_{REF} = 2$V and $V_{R0} = (0.2 \sim 1)V_{RE}$, Fig. 6 shows the effect of V_{R0} and v_K on K estimated with expression (28).

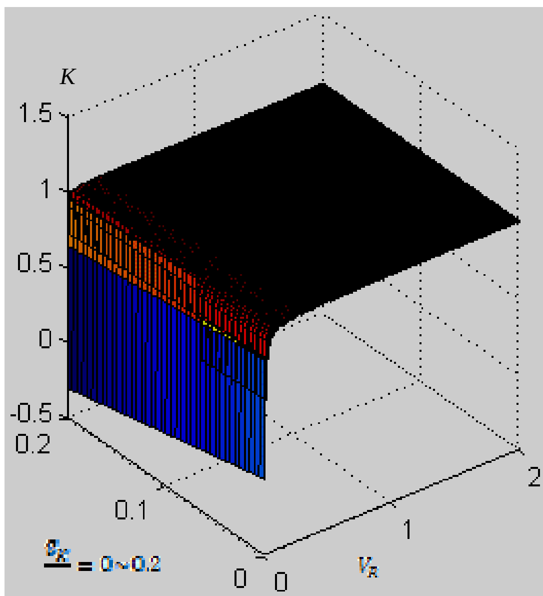


Fig.6 Relationship among K, V_R, and v_K

Fig.(6) shows that the K obtained from expression (28) is almost the same when $V_{R0} \geq 0.5V_{REE}$ and the effect of $\bar{v}_K$ could be ignored.

The compensation method is called average parameter compensation method (APC) since a and $\bar{v}_K$ are average values.

VI. CONCLUSION

A portable data acquisition could be designed with a smart phone and the smart phone is a digital signal process core which can increase measurement accuracy. A simple compensation method proposed called APC is useful for measurement system with smart phone. With average parameters APC has make a good compensation for measurement result and reduced most of measurement errors.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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