Digitally Programmable AC Current Source

Wandee Petchmaneelumka, Apinai Rerkratn, and Anucha Kaewpoonsuk

Abstract—In this paper, a digitally programmable AC current source is introduced. The proposed technique provides the ability of digital trimming the output current frequency and amplitude. The realization method based on commercially available devices employs digital-to-analog converter (DAC), voltage controlled oscillator (VCO), digital gain amplifier (DGA), and voltage controlled current source (VCCS). The proposed circuit offering high accuracy and linearity is suitable for measuring biompedance measurement. Experimental results showing the circuit performances are also included.

***Index Terms*—VCCS, current source, voltage-to-current converter, CCII-based circuit.**

I. Introduction

Bioimpedance measurements are widely used in medical applications such as respiratory monitoring, gastric emptying measurement, and cardiac output monitoring. For measuring unknown impedance, there are two possible approaches. Firstly, a known voltage is applied across an object. Then the current flowing through it is measured. Secondly, a known current is injected into the object and then the voltage across it is measured. The impedance of each approach can be achieved by using Ohm's law. In the past, the bioimpedance measurements based on the second approach have been reported [1]-[3]. The AC current source with adjustable frequency in wide range is one of the important problems to be considered [4]. The current source reported in [4] consists of a microcontroller, a programmable waveform generator, and a VCCS based on the enhanced Howland circuit. However, the enhanced Howland circuit requires the critical matching resistor conditions [5]. The aim of this paper is to present an inexpensive method to implement the digitally programmable AC current source for bioimpedance measurements. No critical matching condition is required in the proposed technique. The amplitude and frequency of the AC output current can be independently varied in the ranges of 40μA – 10mA (peak-to-peak) and 1kHz – 100kHz, respectively.

II. The Proposed System

Block diagram of the proposed AC current source is shown in Fig. 1. It comprises (a) 8-bit digital-to-analog converter (DAC), (b) voltage controlled oscillator (VCO), (c) digital gain amplifier (DGA), and (d) CCII-based voltage controlled current source (VCCS). The frequency and amplitude of the output current can be varied by 16-bit control data. The first 8-bit data (A1 - A8) are used to control the current frequency whereas the last 8-bit data (B1 – B8) are employed to control the current amplitude. The first 8-bit data applied to DAC are converted into the DC voltage. This DC voltage is employed to generate the sinusoidal signal by the operation of the VCO. The rate of repetition of the sinusoidal signal then becomes the output current frequency. The sinusoidal signal from the VCO and the last 8-bit data are supplied as the inputs of the DGA. The DGA output voltage will be the amplitude control signal for generating output current. The operation of the proposed current source can be explained as follows.

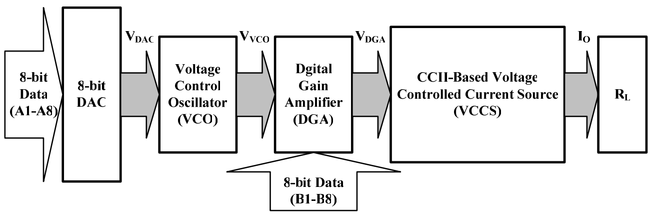

Fig. 1 Block diagram of the proposed digitally programmable AC current source.

A. *Digital-to-analog converter (ADC)*

The circuit diagram of the 8-bit DAC in Fig. 2 consists of the DAC0800 and LF351 devices.

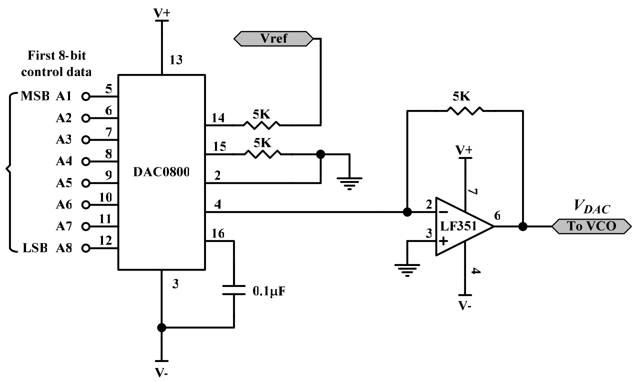

Fig. 2 Digital-to-analog converter.

This DAC converts the digital data A1 – A8 into the DC voltage V_{DAC}, which can be stated as

$$V_{DAC} = V_{ref} * \left(\frac{A1}{2} + \frac{A2}{4} + \frac{A3}{8} + \frac{A4}{16} + \frac{A5}{32} + \frac{A6}{64} + \frac{A7}{128} + \frac{A8}{256} \right) \quad (1)$$

Manuscript received December 27, 2008.

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where V_{ref} is the reference voltage used to define the maximum DC voltage. If $V_{ref} = 3$V is chosen then the voltage V_{DAC}, the control voltage of VCO, will be in the range of 0 - 3V.

B. Voltage controlled oscillator (VCO)

Fig. 3 displays the VCO based on commercial XR-2206 V/F device. The signal V_{VCO} is the sinusoidal waveform with the frequency f_o.

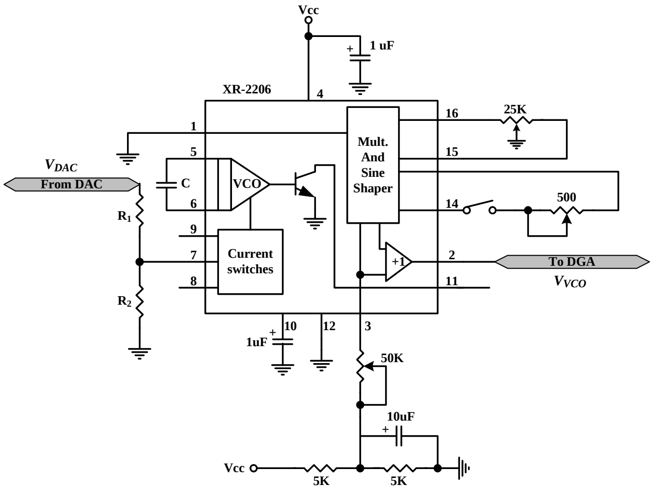


Fig. 3 Voltage controlled oscillator.

The relation between the frequency f_o and the voltage V_{DAC} can be given by

$$f_o = \frac{1}{R_2 C}\left(1 + \frac{R_2}{R_1}\left(1 - \frac{V_{DAC}}{3}\right)\right) \tag{2}$$

From (2), it is evident that increasing V_{DAC} decreases the frequency. Thus the voltage - frequency relation of the VCO in Fig. 3 is negative. To obtain the suitable frequency range 1kHz – 100kHz for bioimpedance measurement, we design the circuit such that $R_1 = 2\text{k}\Omega$, $R_2 = 100\text{k}\Omega$, and $C = 10$nF. This means that the 100kHz and 1kHz frequencies can be generated by applying the DAC data as 0000 0000 and 1111 1111, respectively. The amplitude of the signal V_{VCO} can be tuned via the variable resistor connected at pin 3. In this paper, the signal V_{VCO} with 5Vp-p amplitude is chosen.

C. Digital gain amplifier (DGA)

The implementation based on the DAC0800 and LF351 devices of the DGA is illustrated in Fig. 4. The voltage V_{DGA} can be expressed as

$$V_{DGA} = \left(\frac{\text{B1}}{2} + \frac{\text{B2}}{4} + \frac{\text{B3}}{8} + \frac{\text{B4}}{16} + \frac{\text{B5}}{32} + \frac{\text{B6}}{64} + \frac{\text{B7}}{128} + \frac{\text{B8}}{256}\right) * R_o * \left[\frac{V_{offset}}{R_{14}} + \frac{V_{VCO}}{R_s}\right] \tag{3}$$

From (3), if $R_o = R_s = R_{14} = 5\text{k}\Omega$ are chosen, then the voltage V_{DGA} can be rewritten as

$$V_{DGA} = \left(\frac{\text{B1}}{2} + \frac{\text{B2}}{4} + \frac{\text{B3}}{8} + \frac{\text{B4}}{16} + \frac{\text{B5}}{32} + \frac{\text{B6}}{64} + \frac{\text{B7}}{128} + \frac{\text{B8}}{256}\right) * \left(V_{VCO} + V_{offset}\right) \tag{4}$$

From (4), it is seen that the voltage V_{DGA} becomes the sinusoidal signal. Its frequency and amplitude are followed by the V_{VCO} frequency f_o and digital data B1 – B8, respectively.

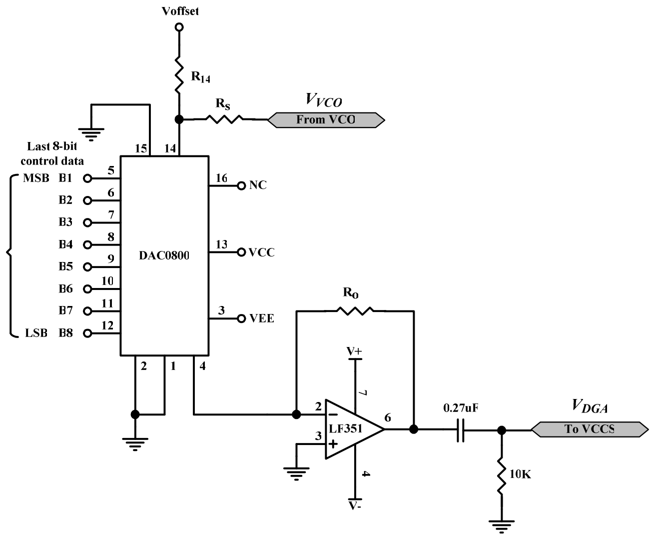


Fig. 4 Digital gain amplifier.

D. CCII-Based Voltage Controlled Current Source

In practical, the AD844 devices configured as the CCII can be formed as the basic VCCS. Nevertheless, the parasitic resistance at port x r_x, dependent on the ambient temperature, is the major factor that contributes the inaccuracy of the basic VCCS. To minimize this limitation, the accurate CCII-based VCCS is shown in Fig. 5 [6].

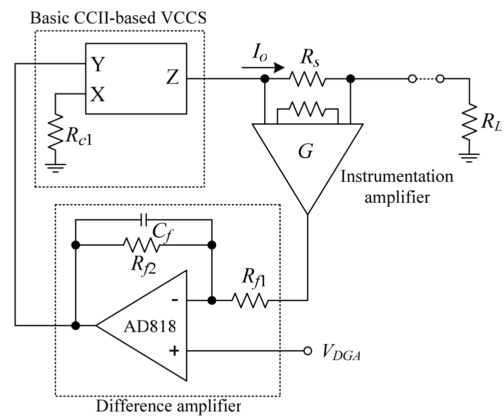


Fig. 5 Accurate CCII-based VCCS [6].

The signal V_{DGA} is applied as the input of the difference amplifier. For realizing the circuit in Fig. 5, we employ AD844, IN103, and AD818 to function as the basic VCCS, instrumentation amplifier, and difference amplifier, respectively. From circuit analysis, the voltage V_{DGA} and the output current I_o can be state as

ISBN: 978-988-17012-7-5

$$I_o = \left(1+\frac{R_{f1}}{R_{f2}}\right)\left(\frac{1}{1+\left(R_{f1}(R_{c1}+r_x)/R_{f2}R_sG\right)}\right)\frac{V_{DGA}}{R_sG} \qquad (5)$$

where G is a voltage gain of the instrumentation amplifier. If we chosen such that $R_{f2} >> R_{f1}$, then the output current I_o can be rewritten as

$$I_o = \frac{V_{DGA}}{R_sG} \qquad (6)$$

From (6), it can be seen that the resistance r_x is eliminated. The circuit characteristic of Fig. 5 is insensitive from temperature variation. If the resistor R_s and the gain G are fixed, the output current then is proportional to the voltage V_{DGA}. If the output I_o flows through the load R_L, the voltage across R_L, V_{RL}, can be given by

$$V_{RL} = I_oR_L = \frac{V_{DGA}R_L}{R_sG} \qquad (7)$$

III. The Experiments and Results

To verify the performances of the proposed technique, the circuits in Figs. 2 ~ 5 were implemented. We used the resistances R_s = 10Ω, R_L = 500Ω and the gain G = 50. Fig. 6 shows the plots of the output current frequency against the first 8-bit digital code. Fig. 7 illustrates the plots of the output current amplitude versus the last 8-bit digital code.

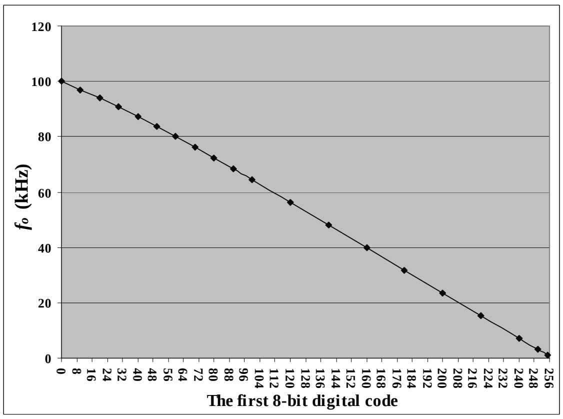


Fig. 6 Plots of the output current frequency f_o against the first 8-bit digital code.

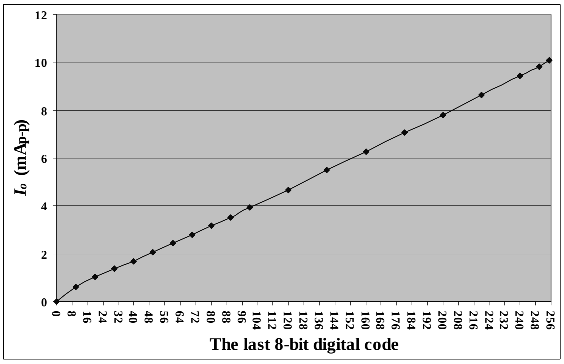
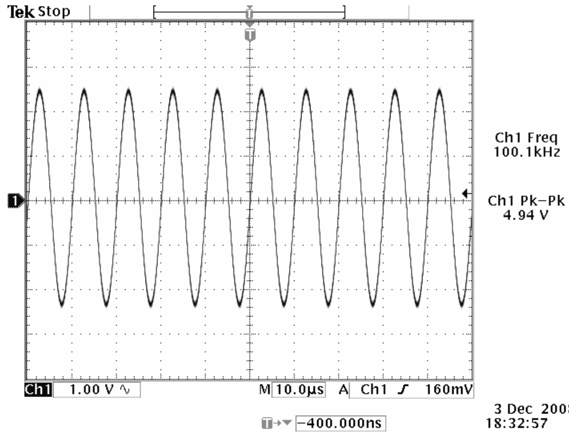
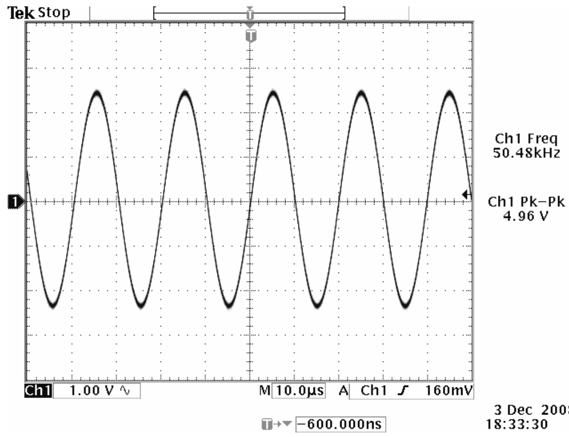


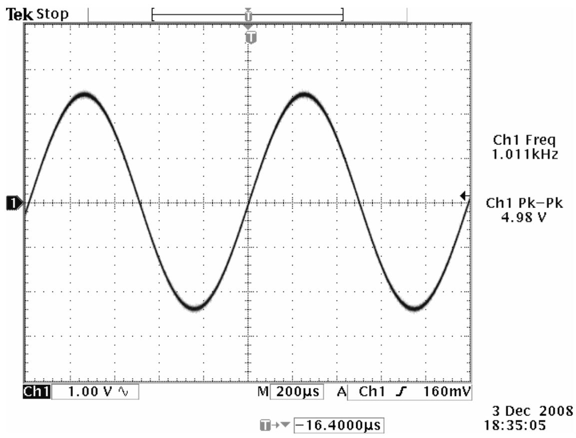
Fig. 7 Plots of the output current amplitude I_o versus the last 8-bit digital code.



(a)



(b)

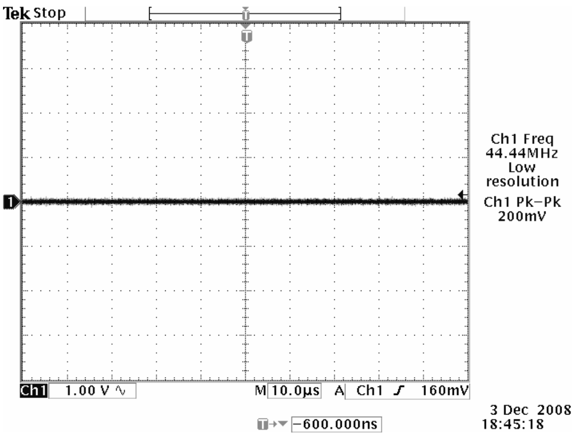


(c)

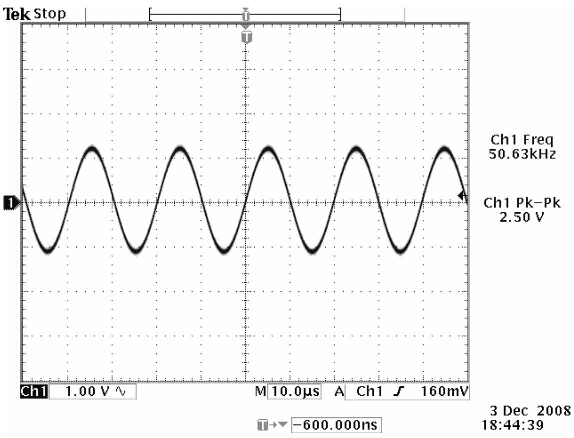
Fig. 8 Measured voltage across R_L for three different digital data (A1 – A8) at 10mAp-p.
(a) digtal data at 0000 0000
(b) digtal data at 1000 0000
(c) digtal data at 1111 1111

From Figs. 6 ~ 7, it is seen that the output current frequency and amplitude can be linearly adjusted by changing digital codes. Fig. 8 shows the measured voltage across R_L at digital data B1 – B8 chosen to be 1111 1111 or 10mAp-p, where the digital data A1 –A8 were set to 0000 0000, 1000 0000, and 1111 1111. In Figs. 8(a) ~ 8(c), the output frequencies of about 100.1kHz, 50.48kHz, and 1.011kHz are measured, respectively. Figs. 9(a) ~ 9(c) display the measured voltage across R_L at digital data A1 – A8 set to be

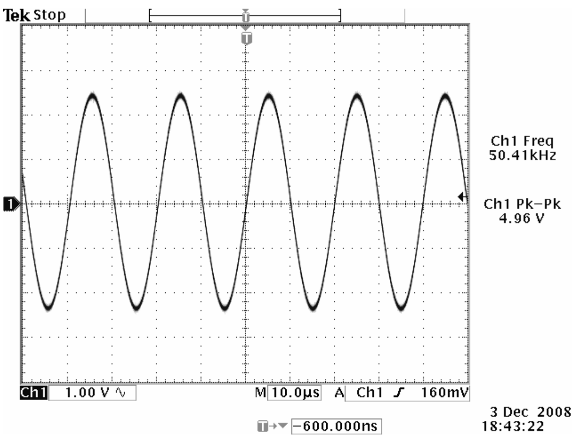
1000 0000 or 50kHz, where three different digital data B1 – B8 0000 0000, 1000 0000, and 1111 1111 were chosen. The amplitude values in Figs. 9(a) ~ 9(c) are about 0, 2.5Vp-p, 4.96Vp-p, respectively. Figs. 10(a) ~ 10(b) show output current at 10kHz and 1mAp-p for varying load resistance from 100Ω to 1kΩ and from 1kΩ to 10kΩ, respectively. It is apparent that the load resistance variation slightly affects to the output current amplitude by using the proposed technique.



(a)

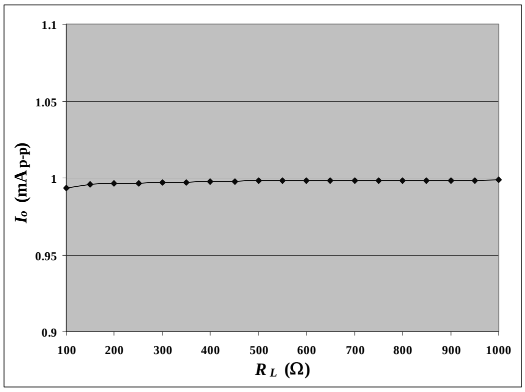


(b)

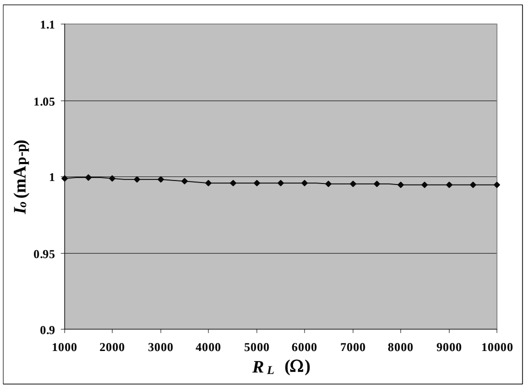


(c)

Fig. 9 Measured voltage across R_L for three different digital data (B1 –B8) at 50kHz.
(a) digtal data at 0000 0000
(b) digtal data at 1000 0000
(c) digtal data at 1111 1111



(a)



(b)

Fig. 10 Output current against the varied load resistance.
(a) load resistance varied from 100 to 1kΩ
(b) load resistance varied from 1kΩ to 10kΩ

IV. Conclusions

The technique without component matching conditions to realize the digitally programmable AC current source for bioimpedance measurements has been developed in this paper. The realization method is based on commercially available devices. Experimental results verify that the proposed technique not only functions correctly but also provides the results in close agreement with the expected values.

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