A Multi-Frequency Current Source For Bioimpedance Application

Kuo-Sheng Cheng, *Senior Member, IEEE*, Cheng-Yu Chen, Min-Wei Huang, and Chien-Hung Chen

***Abstract*—Bioimpedance measurement technology has been widely applied in many biomedical applications such as skin characterization, disease detection, biosensor, etc. The impedance of tissue may be changed due to the varied frequencies. Therefore, the bioimpedance measurement needs to be made over a wide frequency range. In this paper, a multi-frequency current sourece is proposed and designed. It includes (1) a microcontroller, (2) a programmable waveform generator, and (3) a voltage controlled current source (VCCS). The microcontroller is the kernel of the whole system that is used to program the waveform generator to produce the sinusoidal voltage signal over the frequency range of 100 Hz to 100 kHz. Then, this signal is converted to current using the VCCS based enhanced Howland current pump. From the results, the total harmonic distortions of the output current are only 0.25% and 0.40% for the load resistance of 1 kΩ at operational frequency at 1 kHz and 100 kHz, respectively. The phase difference of the output current is within the range of 0 to 19.6° over the studied frequency range. It is shown that the proposed multi-frequency bioimpedance measuring system could provide an inexpensive solution for bioimpedance applications.**

I. INTRODUCTION

Bioimpedance technology has been widely applied in many biomedical applications such as tissue characterization, physiological measurement, disease detection, biosensing, etc. It has the advantages of easy to use, low cost, and fast response. It has also been extended and used for imaging the electrical property inside the body, which is called as impedance imaging or electrical impedance tomography [1][2].

The tissue structure and its contents may exhibit different electrical characteristics. There are many models for describing the electrical characteristics. The often used electrical models for tissue are three-element and four-element models. The circuit representation of three-component is depicted in Fig 1.

Due to the nature of tissues, the impedance may vary with the frequency of measuring signal. The impedance will decrease as the frequency increases. The relationship between the impedance and frequency is nonlinear. Both the resistivity and permittivity are frequency dependent. The higher the frequency, the lower is the impedance. Furthermore, the current pathway in the tissues is different for the varied frequency [2][3]. Thus, a multiple-frequency bioimpedance measuring system plays an important role in the electrical property characterization of tissues.

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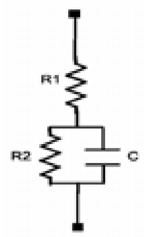

Fig. 1. The 3-element circuit for modeling the tissue electrical property

The currently often used instruments for impedance measurement are the impedance analyzer and LCR meter. Although they have good performances in measurement, they are high cost and inflexible for clinical applications. Therefore, the purpose of this study is to design and develop a bio-impedance measuring system that are low cost and frequency adjustable. The typical specifications of this system are listed in Table 1.

TABLE 1.
THE TYPICAL SPECIFICATIONS OF CURRENT SOURCE FOR MULTI-FREQUENCY BIOIMPEDACNE APPLICATIONS

	Multi-frequency current source
Operation Freq.	0.1 - 100 kHz
Current amplitude	0.5 - 1 mA with 12bits accuracy
Measuring method	2-electrodes

II. SYSTEM DESIGN

The block diagram of this proposed system is shown in Fig 2. The microcontroller is used as the kernel for programming the waveform generator to produce the sinusoidal voltage signal with the frequency range from 100 Hz to 100 kHz. Then, it is converted to current by the voltage-controlled-current-source (VCCS for short) based enhanced Howland current pump. Then, the commercially available multi-meter and phase meter are employed for impedance measurement at different frequencies.

The proposed multi-frequency current source includes (a) a microcontroller and its control interface, (b) a programmable waveform generator, and (c) a VCCS based current source. These parts will be described in the following.

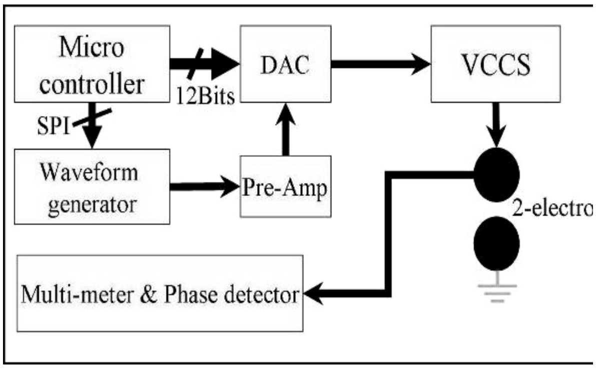

Fig. 2. The block diagram of the proposed system

A. *A Microcontroller and its control interface*

The microcontroller is used to set the amplitude and frequency of output signal. Besides, a digital control interface circuit is also designed for it to control the D/A converter. It has the advantages such as low setup steps and extensible control ability (PC based control interface). The block diagram of this circuit is shown in Fig 3.

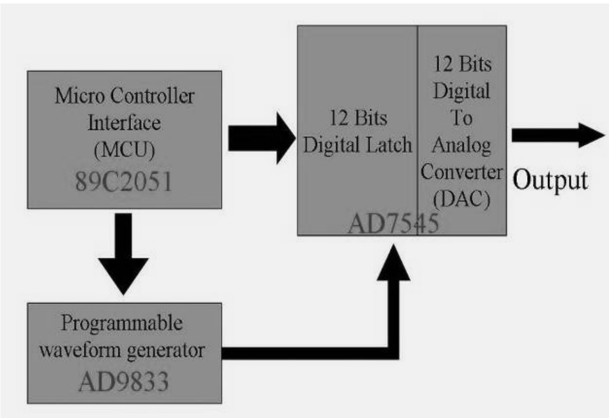

Fig. 3. The block diagram of microcontroller interface and its control interface

The microcontroller can communicate with the programmable waveform generator by a serial data transmission interface. It may program the waveform generator to synthesize the output signal with different frequency. It also controls the digital to analog converter (DAC). The DAC is used to set the signal amplitude that directly relates to the output current level.

B. *A Programmable waveform generator*

For multi-frequency bioimpedance applications, the current source needs to set the current with different frequency. AD9833 (Analog Device Inc.) is a programmable waveform generator. Its major specifications are listed in Table 2, and its typical application circuit is depicted in Fig 4. The microcontroller transmits the data to the internal register of

TABLE 2.
THE MAJOR SPECIFICATIONS OF AD9833

	AD9833
Output frequency range	0 - 12.5 MHz
Waveform type	Square/Triangular/Sinusoidal waveform
Control method	Digital SPI interface

AD9833 via the SPI interface. The AD9833 may then synthesize voltage waveform with different frequency.

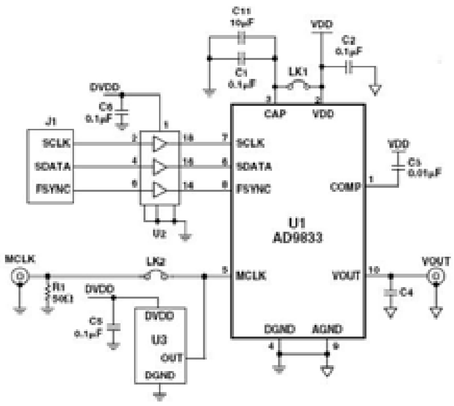

Fig. 4. The AD9833 application circuit [6]

The phase shift of waveform is also programmed through the same method. The data for the frequency register is computed using Eq. (1) as

$$f_{MCLK} / 2^{28} \times FREQREG \tag{1}$$

Similarly, the data for phase shift register is computed by Eq. (2) as

$$2\pi / 4096 \times PHASEREG \tag{2}$$

The different frequencies relate register data are listed in Table 3.

TABLE 3.
THE OUTPUT FREQUENCY VS. THE VALUE OF FREQREG

Output frequency (Hz)	Data value (Hex)
100	0000431
500	00014F8
1 k	00029F1
5 k	000D1B7
10 k	001A36E
50 k	0083126
100 k	010624D

C. The voltage control current source (VCCS)

The current sources are usually designed and constructed using the following types of circuit: (1) the current mirror type, (2) the multi-Op Amps feedback type, and (3) the enhanced Howland circuit [1][4].

The structure of enhanced Howland circuit is very simple and its performance is predictable [4]. Hence, the enhanced Howland circuit is employed here for the circuit of current source. The schematic diagram of enhanced Howland circuit is shown in Fig. 5.

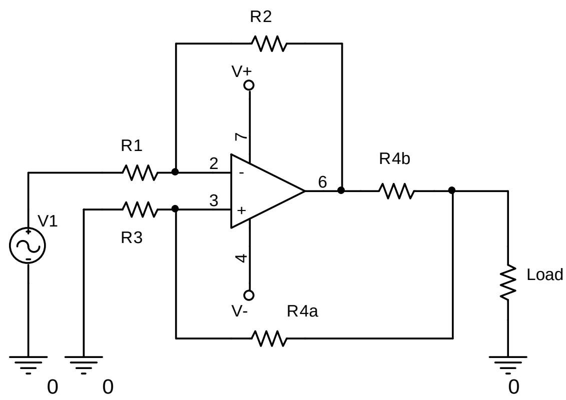

Fig. 5. The enhanced Howland circuit

For completeness, the mathematical derivation of enhanced Howland circuit is described as follows. The output current I_L of this circuit is given as Eq. (3):

$$I_L = -\frac{V_1}{R_{4b}}\frac{R_2}{R_1} \qquad (3)$$

The output current I_L is set by voltage signal V_1 and resistance ratio R_2 / R_1, as well as the current sensing resistor R_{4b}. Thus, it is independent of load resistance. Its ideal output impedance is obtained using Eq. (4):

$$R_{out} = \frac{R_1 R_{4b}(R_3 + R_{4a})}{R_2 R_3 - R_1(R_{4a} + R_{4b})} \qquad (4)$$

When the resistance ratio meets the condition given in Eq. (5):

$$R_2 R_3 = R_1(R_{4a} + R_{4b}) \qquad (5)$$

The ideal output impedance will approach to infinite. That is to say, the performance of current source may be very good for bioimpedance applications.

In enhanced Howland circuit, the low noise OP amp LM833 (National Semiconductor Inc.) is used. From the circuit simulation results, this circuit may be operated at frequencies lower than 100 kHz. The output impedance is presented in Table 4.

TABLE 4.
THE OUTPUT IMPEDANCE OF THE ENHANCED HOWLAND CIRCUIT WITH A LOAD RESISTANCE OVER 100 Ω TO 1 KΩ

Frequency (Hz)	LM833 based circuit Z_{out} (Ω)
1 k	30 M
10 k	13 M
50 k	1.8 M
100 k	517 k
200 k	145 k
300 k	63 k
1 M	1.6 k

III. EXPERIMENTAL RESULTS

The picture of the proposed multi-frequency current source and digital multimeter for the bioimpedance measuring system is shown in Fig. 6.

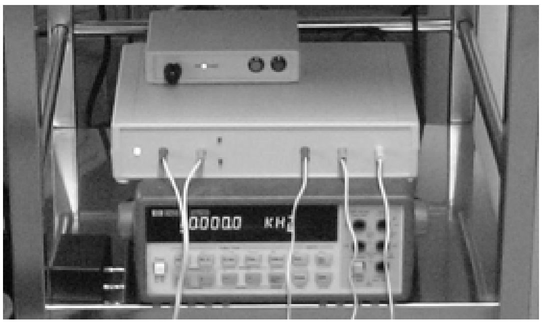
Fig. 6. The multi-frequency bio-impedance measuring system

The system performance is evaluated by different parts measurement. Firstly, the output stability of the waveform generator over the studied frequency range is investigated. The output voltages with different frequencies for this circuit are listed in Table 5. From the results, the synthesized waveforms for AD9833 are very precise both in frequency

TABLE 5.
THE OUTPUT STABILITY OF AD9833

Setting Freq. (Hz)	Vrms (mV)	Vp-p (mV)	Measured Freq. (Hz)
100	219	624	99.90
500	219	624	500.0
1 k	219	624	1.000 k
5 k	218	628	4.995 k
10 k	218	628	10.01 k
50 k	218	628	49.90 k
100 k	219	632	100.1 k

and voltage.

Then, the current output of VCCS is tested for varied load resistances. The output currents for the load resistance ranges at 20 kHz is shown in Fig 7. The error of output current is about 0.25%.

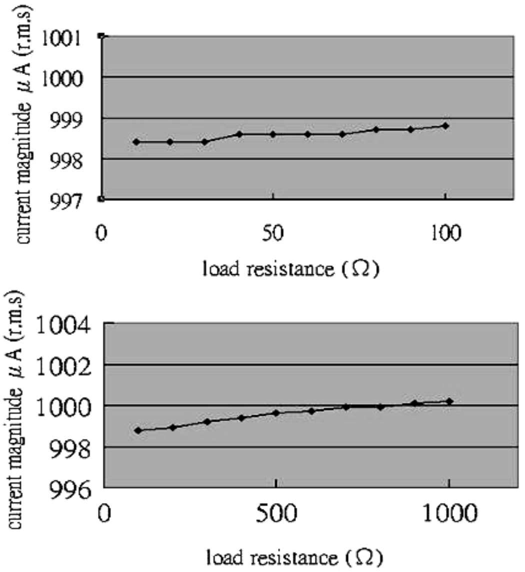

Fig. 7. The output current for varied load resistance range at 20 kHz

Furthermore, total harmonic distortion (THD) and phase shift are also used to verify the system performance of current source at varied frequency. Under the load resistance of 1 kΩ and the operating frequency from 100 to 100 kHz, the THD is estimated for up to sixth harmonics using Eq. (6):

$$THD = 20\log\sqrt{\frac{(V_2^{\,2} + V_3^{\,2} + \cdots + V_n^{\,2})}{V_1}}$$

$$THD = \sqrt{\frac{(V_{O2}^{\,2} + V_{O3}^{\,2} + \cdots + V_{On}^{\,2})}{V_{O1}^{\,2}}} \times 100\% \quad , n=6 \qquad (6)$$

The results of THD at different frequencies are listed in Table 6. The results of phase delay between the waveform generator

TABLE 6.
THE TOTAL HARMONIC DISTORTION OF THE PROPOSED CURRENT SOURCE

Freq. (Hz)	THD (dBc)	THD (%)	Freq. (Hz)	THD (dBc)	THD (%)
100	-52.3	0.245	10k	-52	0.244
500	-51.3	0.273	50k	-51	0.279
1k	-52.4	0.241	100k	-48	0.396
5k	-53.3	0.217	--	--	--

and the output current source are presented in Table 7. The

TABLE 7
THE PHASE DELAY OF SIGNAL BETWEEN THE WAVEFORM GENERATOR AND VCCS

Freq. (Hz)	100	500	1k	5k	10k	50k	100k
Phase delay (degree)	0	0	0	0	0	7.9	19.6

maximal value is about 19.6°.

When the proposed current source is loaded with a 1 kΩ resistance at the operating frequency of 1 kHz, the total harmonic distortion (THD) of output current is 0.248%. The phase difference between the output current and the signal of waveform generator has no delay. At 100 kHz, the THD of output current is 0.396%, and the phase delay is 19.6°.

From the results, the proposed current source has better performance at low operating frequency than that at high frequency. This may due to the slow rise time of active components in this circuit. It may be improved by using high-speed components.

IV. DISCUSSION AND CONCLUSION

From the experimental results, it is shown that the proposed multi-frequency bio-impedance measuring system could provide good performance over the frequency range of 100-100 kHz. Although the output signal may have the delay from 0 to 19.56°, this may be compensated using software approach. The total harmonic distortion of the output signal is also quite good for some clinical applications. In general, the output current signal is very stable during system testing.

The microcontroller provides a flexible digital control interface to the personal computer. Either the RS232 or USB port may be used for data transmission through the graphic user interface of PC.

The proposed system may be applied to the clinical application such as the electrical characterization of skin tissues for disease detection.

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