Characteristics of the Howland current source for Bioelectric Impedance Measurements Systems

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Abstract—**In the development of bioelectric impedance measuring systems, design of a stable current source with broad bandwidth and high output impedance is an important consideration. Howland circuit is a well known high performance, voltage controlled current source which can provide high output impedance as well as high frequency bandwidth. This paper presents a detailed study of Howland current source by considering the non-ideal characteristics of the components. Two different forms of Howland current source are compared and resulted relationship were evaluated by simulations. The results of this study facilitate the design of Howland circuit for bioelectric impedance measurement systems.**

Keywords: Bioelectric impedance; Current Source; Howland circuit; Impedance Plethysmography; Impedance Spectroscopy

I. INTRODUCTION

Bioelectric impedance (BEI) measurements is a noninvasive method of inferring biological information from a part of the body, and have a long history of more than a hundred years [1]. BEI measurements can be classified into two types of Impedance plethysmography and impedance spectroscopy. The first which is more common measures the small pulsatile impedance changes associated with heart and respiratory function. The second however, involves the determination of body characteristics such as total body fluid volume, inter and extra-cell volume, percent body fat, and cell and tissue viability [1].

BEI measuring systems usually consist of a current source to inject a controllable amount of current to the tissue and a voltage sensor to measure the developed voltage across the tissue due to the injected current and therefore the impedance of the tissue [2]. Injecting current instead of applying voltage is more common for measuring the impedance, since the safety can be maintained more easily with the current amplitude [3]. Different types of the current sources have been used in BEI measuring systems, among them the Howland current source (HCS) have remained a popular choice. HCS is a high performance voltage controlled current source (VCCS) based on a single operational amplifier (Op-Amp) and a few resistors. Various configurations of HCS have been used for the bioimpedance measurement [4], tissue characterization[5], electrical impedance tomography (EIT) [6], and diagnosis of the breast cancer [7]. The broad ranges of applications of the HCS have interested several researchers to study the characteristics and performance of this current source.

Chen et al. [8] and Xiaoke et. al [9] have compared three variations of HCS for their performance. However, their study has been limited to the output impedance of the current source and its stability over the frequency.

Zhao [10] has analyzed the frequency and time domain characteristics of the standard HCS(Fig.1) to design a proper current source for EIT. He concluded that the performance of the HCS can be improved by precise selection of appropriate amplifier, and the peripheral components.

Hammond et al. [11] have presented a comprehensive noise analysis of the HCS by considering Janson thermal noise of the resistors and the voltage/current noise of the amplifier. They found that the basic HCS has lower noise than the standard configuration while the temperature sensitivity of the amplifier is lower in standard HCS.

BEI measuring systems require a current source with stable output current, high output impedance, and broad bandwidth. This paper presents a comprehensive analysis of the HCS for its application in BEI. In section II, a detailed analysis of the standard HCS is presented by considering the non-ideal characteristics of the Op-Amp and mismatch of the resistors. In section III, the standard and basic forms of HCS are compared. Finally, the calculated relationships were evaluated in section IV using a series of simulations performed in TINA simulation software.

II. STANDARD HCS CIRCUIT

Fig.1 illustrates the standard HCS. The positive and negative feedback paths are balanced when the resistors are matched according to (1):

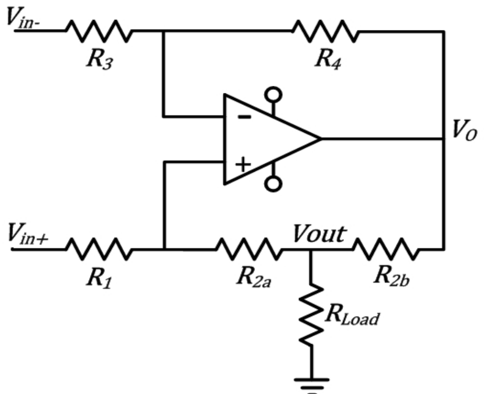

Figure 1 Standard Howland Current Source

$$\frac{R_{2\mathrm{a}}+R_{2\mathrm{b}}}{R_1}=\frac{R_4}{R_3} \tag{1}$$

In this case the circuit becomes a voltage-controlled current source (VCCS) and the load current is independent of its voltage and is proportional to the differential input voltages:

$$\frac{I_{\mathrm{Out}}}{V_{\mathrm{in+}}-V_{\mathrm{in-}}}=\frac{1}{R_{2\mathrm{b}}}\frac{R_4}{R_3}=\frac{1}{R_{2\mathrm{b}}}\frac{1-\beta_{\mathrm{fb}}}{\beta_{\mathrm{fb}}} \tag{2}$$

Where, $\beta_{\mathrm{fb}}=R_3/(R_3+R_4)$;

However, in practice imperfect resistor balancing due to the tolerance of the resistors as well as the non-ideal behavior of the Op-Amp can degrade the performance of the HCS.

A. The effect of tolerance of the resistors

The Howland circuit requires tight matching of the resistors for appropriate performance. It can be shown that violation of the criterion (2) result in finite output resistance of the HCS. If we assume the worst-case mismatch resistors scenario, the minimum output resistance can be written as:

$$R_{\mathrm{out}}=\frac{(R_1+R_{2\mathrm{a}})\|R_{2\mathrm{b}}}{1-\beta_{\mathrm{fb}}}\frac{(1-T)^2}{\pm 4T} \tag{3}$$

Where, T is the tolerance of the resistors.

The equation imply that, to achieve high output resistance, one has to select low-tolerance resistors, large feedback ratio(β_{fb}), large $R_{2\mathrm{b}}$, and large resistors in design,

B. Offset voltage and bias current of the Op-Amp

Considering the input offset voltage and bias current of the Op-Amp, the input-output relationship for HCS can be written as:

$$I_{\mathrm{out}}=\frac{1-\beta_{\mathrm{fb}}}{\beta_{\mathrm{fb}}R_{2\mathrm{b}}}(V_{\mathrm{in+}}-V_{\mathrm{in-}})+\frac{1}{\beta_{\mathrm{fb}}R_{2\mathrm{b}}}V_{\mathrm{off}} -\frac{1}{R_{2\mathrm{b}}}(R_4 I_{\mathrm{b-}}-R_2 I_{\mathrm{b+}}) \tag{4}$$

This equation implies that the use of larger values for $R_{2\mathrm{b}}$ can improve the DC performance of the HCS. In addition, using equal resistors for negative and positive feedback paths and large β_{fb} minimize the output error.

C. Finite Op-Amp open loop gain

The Op-Amp's finite open loop gain, A_{OL} , is another factor that limits the precision of the HCS circuit. Especially for high frequencies where the A_{OL} decreases, the output impedance of the current source decreases significantly. The output impedance of the Howland circuit can by calculated as:

$$R_{\mathrm{out}}=(R_{2\mathrm{b}}\|(R_1+R_{2\mathrm{a}}))(1+A\beta_{\mathrm{fb}}) \tag{5}$$

Equation (5) states that the output resistance of the circuit can be improved by larger feedback ratio and larger resistors.

D. Finite Op-Amp bandwidth

The finite gain band width product (*GBW*) of the Op-Amp is another factor that degrades the HCS output impedance. This is particularly important for frequencies above 10 kHz [12] which includes the BEI metering and impedance plethysmography. To obtain a relationship for the output impedance, the classic first order relationship for the Op-Amp gain was considered:

$$A_{OL}(j\omega)=\frac{A_{\mathrm{OL}}}{1+j\dfrac{\omega}{\omega_{\mathrm{b}}}} \tag{6}$$

Where $A_{\mathrm{OL}}$is the DC open-loop gain and ω_{b} is the cut off frequency of the Op-Amp. By substituting (6) in (5) the output impedance of the HCS is calculated as:

$$Z_{\mathrm{out}}=(R_{2\mathrm{b}}\|(R_1+R_{2\mathrm{a}}))(1+A\beta_{\mathrm{fb}})\left(\frac{1+j\dfrac{\omega}{\omega_{\mathrm{b}}(1+A\beta_{\mathrm{fb}})}}{1+j\dfrac{\omega}{\omega_b}}\right) \tag{7}$$

Equation (7) states that the actual output impedance of the current source decreases with the frequency, with the same cut-off frequency as for the Op-Amp gain.

E. Slew rate

Here, the slew-rate of the HCS is defined as the maximum rate of change of the output current. To obtain this, the output current was rewritten with respect to the output voltage of the operational amplifier, and then its differential was derived. Considering $V_{\mathrm{in+}}$=0 for simplicity, the slew rate would be at the worst case and can be obtained from the following equation:

$$\frac{SR_{\mathrm{HCS}}}{SR_{\mathrm{opamp}}}=\frac{1}{R_{2\mathrm{b}}+Z_{\mathrm{L}}\left(1+\dfrac{R_{2\mathrm{b}}}{R_1+R_{2\mathrm{a}}}\right)} \tag{8}$$

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This suggests using large resistors in comparison to the load and also a small R_{2b}, in order not to lose the slew rate of the Op-Amp.

F. Noise

Here, the Johnson thermal noise of the resistors, the input current noise density, i_n, and the input voltage noise density, e_n, was considered, and the equivalent input noise of the HCS circuit was calculated as follows:

$$E_n = \sqrt{\left(4kT\frac{R_1+R_3}{1-\beta_{fb}} + i_n^2(R_1^2+R_3^2) + e_n^2\frac{1}{(1-\beta_{fb})^2}\right)BW_{eq}} \quad (9)$$

where, BW_{eq} is the equivalent bandwidth of the circuit.

III. Comparing between Standard and Basic HCS

Fig.2 demonstrates the schematics of the basic HCS. In this special configuration of the standard HCS, the R_{2a} is equal to zero and R_{2b} is equal to R_2. Therefore, the output current can be written as:

$$\frac{I_{Out}}{V_{in+} - V_{in-}} = \frac{1}{R_2}\frac{R_4}{R_3} = \frac{1}{R_1} \quad (10)$$

It can be seen from (10) that the gain of this circuit is, the minimum gain of the standard HCS circuit. This is a disadvantage of the basic HCS when high gain and high input impedance are desired simultaneously.

Furthermore, in this topology the power consumption of the R_1 and R_3 is increased. This may lead to changes in their values which may unbalance the criterion (2) and degrade the performance of the circuit [9].

Another weakness of the basic HCS is its limited output compliance in comparison to the standard configuration [13].

The worst-case output resistance of the basic HCS due to the tolerance of the resistors can be calculated by substituting zero for R_{2a} in equation (3):

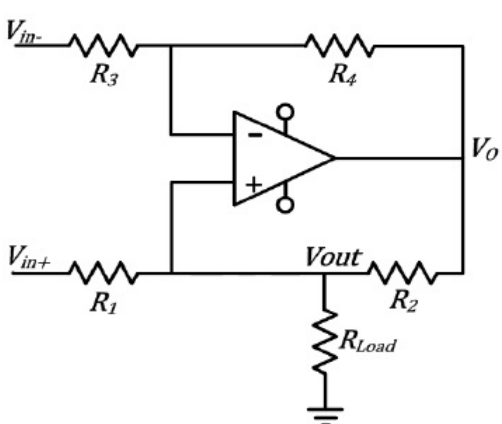

Figure 2 Basic Howland Current Source

$$R_{out} = R_1\frac{(1-T)^2}{\pm 4T} \quad (11)$$

quation (11) states that the use of larger R_1 increases the output impedance while it also decreases the gain of the circuit.

In the previous section, it was shown that the output error caused by input offset voltage and bias current can be kept small by using larger R_{2b} (equation 4). In addition, when open loop gain of Op-Amp is finite, according to (5), large values of R_{2b} improves the R_{out}. Therefore, the basic HCS topology minimizes the error of output current caused by input offset voltage and bias current of the Op-Amp as well as maximizes the R_{out} due to the finite gain in comparison with the standard HCS.

On the other hand, according to (8) the slew rate of the basic HCS is the minimum of the standard configuration.

Table I presents the summarized comparison between basic and standard HCS.

Table I Qualitative comparison between Basic and Standard configuration

Parameter	Basic	Standard
Gain		Higher
Compliance		Higher
Output Impedance	Higher	
Output Current Error(offset-bias)		Higher
Slew rate		Higher
Components	4 Res+ 1 Amp	5 Res+ 1 Amp

IV. Simulations

In this section, the relationships derived in section II and section III is validated by the simulations performed using TINA electronic circuit simulation environment (SoftDesign). Two 10 KHz sine wave of 1 Vp-p and 180° phase difference was applied as inputs to the circuit where $R_1 = R_2 = R_3 = R_4 = 10\ \mathrm{k\Omega}, R_{2a} = R_{2b} = 5\ \mathrm{k\Omega}$, and $R_{load} = 50\ \Omega$. For the basic configuration, the resistor values were $R_1 = R_3 = 5\ \mathrm{k\Omega}$, $R_2 = R_4 = 10\ \mathrm{k\Omega}$ and, $R_{load} = 50\ \Omega$, to have a current source with the same gain as of the simulated standard HCS.

To evaluate the equations that describe the effect of non-ideal Op-Amp, the specifications of the general purpose 741 Op-Amp was used, while for the rest of the equations the Op-Amp was considered ideal as assumed in the derivation of the equations. The supply voltage of the Op-Amp was set to ±15 V. For the selected resistor values and the applied inputs, the output current for both tested configurations was a 400 µAp-p sine wave with the frequency of 10 kHz.

Table II compares the HCS characteristics as obtained from the relationships and the simulations: The results confirm the accuracy and the usefulness of the derived relationships. The results that accounts for the tolerance of the resistors were obtained in theory in the worst cases, while in the simulations, the results were obtained by repeating the related simulation 100 times with resistors that randomly selected based on the considered tolerance. This may describe the difference between the theoretical and simulation results.

Table II Comparison of the HCS characteristics obtained from the relationships with those measured in the simulations.

Configuration	Theory	Equation No.	Simulation
***Output Resistance (Resistor Tolerance, T=10%)*-kΩ**			
Standard	15.185	(3)	15.69
Basic	10.125	(11)	11.14
Output Current Errors due to the Input Offset Voltage (V_{off}=5 mV) and the Input Bias Current (I_{b-}=500 nA, I_{b+}=300 nA) - µA			
Standard	1	(4)	1.2
***Output Resistance (Finite Gain, A(10 kHz)=100)*- kΩ**			
Standard	187.5	(5)	187.5
Slew Rate (Op-Amp Slew Rate=0.5 V/µS)-A/s			
Standard	98.68	(8)	97.8
Noise (i_n=2 pA/$\sqrt{\text{Hz}}$, e_n=25 nV/$\sqrt{\text{Hz}}$)- µV/$\sqrt{\text{Hz}}$			
Standard	6.289	(9)	6.9

Fig.3 shows the effect of the finite gain on the output impedance for basic and standard configurations. The figure was obtained using LM741 model, and shows that the output impedance of the basic HCS is lower than of the standard HCS (In order to have the same gain in both the configurations, R_1 in Standard configuration was set to 10 kΩ, whereas in the basic form it was 5 kΩ).

Fig.4 shows the effect of the resistors tolerance on the output impedance for standard configurations. The figure was obtained using LM741 model and resistors with tolerance of 10%. It can be seen from Fig. 4 that the resistors mismatch can significantly degrade the output impedance of circuit. This is a very important consideration in the design of BEI measuring systems.

From Fig.3 and Fig.4, it can be noticed that the suitable output impedance for BEI measuring systems is achievable when the configuration of HCS, the tight matched resistors and the Op-Amp are selected carefully.

V. CONCLUTION

In this paper, theoretical relationships were derived for the basic and standard Howland current sources to help designing optimum current sources in different application, specifically the BEI measuring systems.

The performance of the standard HCS was studied considering the non-ideal characteristics of the components, including the output offset, impedance and the slew rate. The equations were written in a special form to show that the main characteristics of the HCS can be designed by selecting three main parameters of the circuit: the feedback ratio (β_{fb}), the value of R_{2b}, and the selected scale for the resistors.

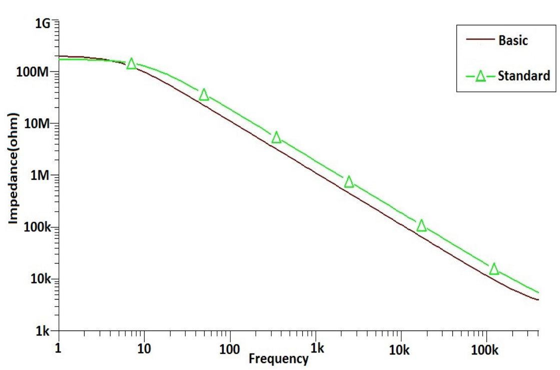

Figure 3 Effect of the finite open-loop gain of the Op-Amp on the output impedance of the circuits.

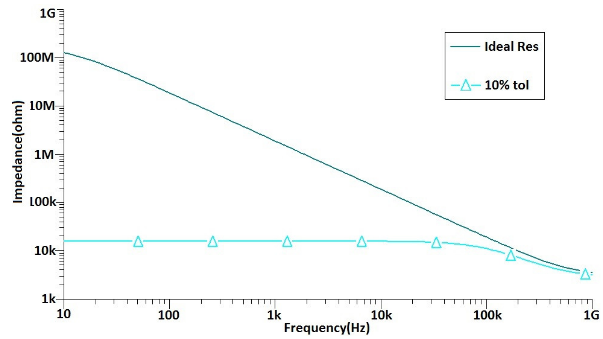

Figure 4 Effect of the tolerance of the resistors on the output impedance of the circuits - T=10%

The equations were compared with those for the basic HCS, which showed that the gain and compliance are minimum, but the output impedance is larger in the basic HCS in comparison with the standard HCS. In addition, the basic configuration minimizes the static output errors.

The derived equations were confirmed by the results obtained from simulations.

Special care must be take in matching the resistors in the circuit, as this leads to a significant reduction in the output impedance of the HCS, a very important parameter in BEI measurement systems. In discrete implementation of the circuit, the use of trimmed resistor arrays is recommended. Another idea is to use “difference” or “instrumentation” amplifiers to benefit from their integrated trimmed resistors.

The results of this study may help to design more optimum current sources for BEI measurement systems.

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