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A Superior Current Source with Improved Bandwidth and Output Impedance for Bioimpedance Spectroscopy

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Abstract: *Electrical Bio-impedance Measurement (EBM)has been widely used as a non-invasive technique for characterizing physiological and pathological status of biological tissues. Voltage Controlled Current Source (VCCS) an important part of the measurement system and its performance directly affects the precision of the measurement. Most widely used current sources in EBM are based on the Howland circuit. In this work we analyze and simulate the driving capability and operating bandwidth of the improved Howland current source. The objective is to design an Operational Transconductance Amplifier (OTA) based VCCS and to compare its performance with other widely used current sources for EBM. The results show that the proposed current source is stable,has wider output current frequency response and output impedance much larger than other current sources for wide frequency range (10kHz to 10MHz).*
Keywords: *Bio-impedance, VCCS, Howland current source, OTA*

I. INTRODUCTION

Electrical Bio-impedance Measurement (EBM) is a widely used technique to measure the impedance of the cellular, skin and human body segments for medical applications. Through two electrodes, known constant amplitude of an alternating current is injected into human tissue and the resulting voltage is measured through two other electrodes to calculate the bioimpedance of the subject under test.EBM is used in measurement of skin impedance[1] (tissues healing rates, skin hydration, etc.), electrical impedance tomography[2], to detect breast cancer[3], bioelectrical properties of blood[4], etc. This technique can also be used for analyzing body composition. The method of EBM is considered fast, inexpensive, practical and efficient. Small size devices, on-chip systems applied to biomedical solutions have made its popularity grow. Most EBM systems consist of applying a multi-frequency sinusoidal current of constant amplitude into the tissue sample, measuring the resulting potential and calculating the impedance.

To ensure accurate and required transfer impedances, a current source is to be designed for injecting a constant amplitude current over wide frequency range. This can be obtained only when the current source has high output impedance. Operational amplifier based current sources with wide bandwidths have been widely developed throughout the literature. Certainly they all have one or the other shortcomings like requirements of the op-amp are mostly ignored or given less importance. But these are important when current source is required to operate at or above 10kHz. The accuracy and compliance of the excitation current can greatly affect the quality and performance of the measurement results and also safety of the patients, since it is the source of all calculations. Therefore, in this paper wefocus on the design of a highly accurate VCCS for bioimpedance measurements.

A current source suitable for EBM is designed and simulated using Cadence OrCADPspice software. Our targeted measuring applications require an operating frequency band of 1kHz to 1MHz and output current much less than 1mA. This paper is organized in following sections

1. Safety and Technical Considerations

The injecting block i.e. current sourceis the most decisive measuring block in EBM system for ensuring precise and safe measurements. All systems that measure transfer impedance from biological tissue require the injection of an electrical current which if not within safety limits, may cause undesirable effects to the patient such as neuromuscular stimulation, cardiac arrest, burning tissue, etc. A current at which sensation may occur is called threshold current. This threshold of sensation rises with increasing frequency of applied current.

Once the current is applied through the skin by surface electrodes, the propagation of a nerve action potential may take place. However, a nerve action potential will not be propagated within one cycle if a higher frequency current is applied. Hence, neural stimulation will not occur. Generally, this is the basis for allowing more current into the body at higher frequencies. The greatest risk is vagal and myocardial stimulation. Either of these can cause ventricular fibrillation. It is concluded [1] that the recommended safe intensity values of the injected current at the body surface should be lower than 1mA at a frequency of 100Hz. It was also pointed out that electrical current higher than $1A_{rms}$ can produce pain, respiratory paralysis, ventricular fibrillation and severe burns.Hence, we aim to achieve a constant current of magnitude below 1mA.

Resistance of body depends upon skin conditions like wet or dry, hydration level of body, temperature and some resistance offered by points of contact.According to [2] the value of skin impedance is between 56Ω and 1916Ω. Adding to this, the resistance of the body varies depending upon points of contact and skin conditions (hydrated or dry). Due to these variations we have used load impedance range from 20Ω to 10kΩ.For BIS measurement the stability of the current source has to be tested for a wide range of frequencies. For lower frequencies, injected current flow through extracellular fluid and for higher frequencies, it flows through intracellular fluid (fluid inside cell). Therefore, the frequency range is chosen between 10 kHz to 10MHz.

2. Howland Model

This current source model is most suitable for bioimpedance measurement as it accounts for the amplifier's limited bandwidth which is an important consideration to make a current source stable.ImprovedHowland model (Fig.1) is very different from other models because it has both positive and negative feedback paths. The feedback paths are balanced when the resistors are matched according to (1).

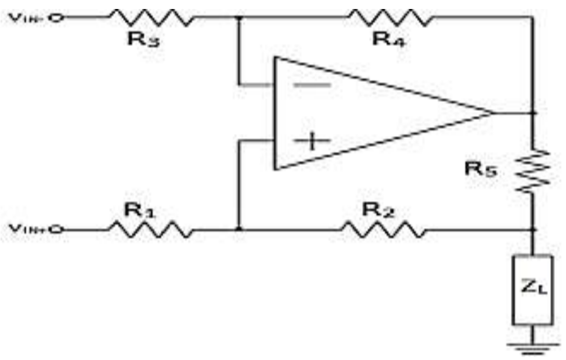

Fig.1. Improved Howland Model [3]

$$\frac{R_4}{R_3} = \frac{R_2 + R_5}{R_1} \quad (1)$$

Much attention has been focused on the effect of resistor mismatchon the Howland source's output impedance. But another importantrequirement of selecting appropriate op-amp is largely ignored, or poorlyunderstood, yet is critical when operating above 10kHz or higher. But mostly, precision of the EBM system depends on the output impedance, Z_o, of the current source which limits the precision of delivered current to the load. For an application requiring 'b' bits of precision in the magnitude of the current, Z_o must satisfy (2) [3].

$$Z_o \geq 2^b (Z_L^{max} - Z_L^{min}) \quad (2)$$

whereZ_L^{max} and Z_L^{min} are maximum and minimum loads considered.

In this work, we have made an improvement in the design of the conventional Howland model by replacing the op-amp by an OTA.An OTA is a voltage input, current output amplifier.Since OTA operates on the principle of processing current rather than voltage, itis an inherently fast device.In OTA, the input circuitry is same as that found in many modern op-amps. The remaining of the circuit is composed of current mirrors of unity current gain. The output current of OTA is given by,

$$I_o = g_m V_{in} = g_m (V_1 - V_2) \quad (3)$$

2.1. Circuit Design

To achieve the desired values of performance parameters (output current, output impedance, etc.) as mentioned in section2, choice of resistors and amplifier plays a very important role.To meet the precision requirement and to avoid mismatch of resistors we have set $R_1 = R_3 = R_4 = 2k\Omega$ and $R_2 = R_5 = 1k\Omega$. A common source of instability is the parasitic capacitance C_1 at op-amp's input terminals. C_2 is feedback capacitor and is connected in parallel with feedback resistor R_4. But C_1 and C_2 should be matched accurately.

C_1 and C_2 are set to 4pf. This is to avoid mismatch of resistors and capacitors and tomeet precision requirement of the current source design for EBM.

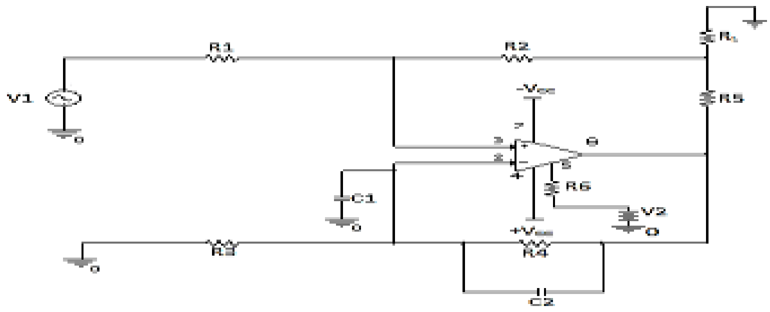

Fig.2. Schematic diagram of simulated OTA based improved Howland model with grounded load

We have modified the improved Howland model using an OTA CA3080. The major controlling factor in the OTA is the external bias current $I_{\mathbf{bias}}$.The input bias current, the input resistance and the output resistance are all proportional to $I_{\mathbf{bias}}$.Output current can be varied easily by just adjusting external bias current, I_{bias}. The maximum output current is equal to $I_{bias.}$ In addition to this, transconductance (g_m), input and output impedance values also vary with this external bias current. This is shown in graph in Fig. 3[4].This simplifies the complexity of calculating output impedance.

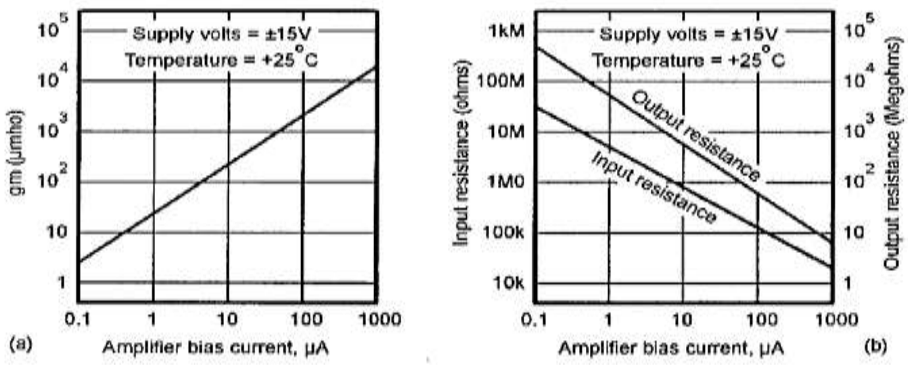

Fig.3. (a) The transconductance and (b) the input output resistances of the CA3080 vary with bias current

The circuit design of proposed current source is shown in Fig.2.It is possible to achieve higher performance with the proposed current source design if high output impedance is obtained.The performance of current source suitable for EBM depends on the output impedance of the current source which limits the precision of delivered current.It is a task to measure the exact value of impedance of a biological material.In practice, the measured impedance (the ratio of measured voltage to the applied current) is a combination of the biological impedance, the electrode/tissue interface impedance and the impedance offered by the drive circuit (VCCS) involved in the measurement. According to (2), the minimum output impedance is about 3.3MΩ [3].

II. SIMULATION RESULTS

The bioimpedance measurement of different parts of human body has been reported in many studies. It has been shown that all living tissues have beta dispersion, in the kilohertz (low) up to Megahertz (high) range, caused by their membranes. To work within safety limits and minimize the effect of dielectric properties of the living tissue, the output current of the circuit was simulated over the frequency range 10 kHz to 10MHz in order to investigate the stability of the circuit at lower and higher frequencies. Most changes between normal and pathological tissues appear in this frequency range.The circuit design of our current source (shown in Fig.2) is simulated using OrCAD Capture 16.6.

As said earlier, the value of skin impedance is between 56Ω and 1916Ω and also the resistance of body varies which depends upon the points of contact and skin conditions whether it is dry or hydrated. Keeping these variations in mind, we have measured the output current over the load impedance range of 20Ω to 10kΩ. Fig.4 shows the magnitude of the output current of proposed OTA based Howland current source, which is around 578μA up to 1MHz when the load changed from 20Ω to 10kΩ. The absolute value of output current is not important because the input voltage of the VCCS circuits can always be changed in order to set the desired output. It is the current stability as the load varies that actually matters and this is determined by the output impedance of the current source.

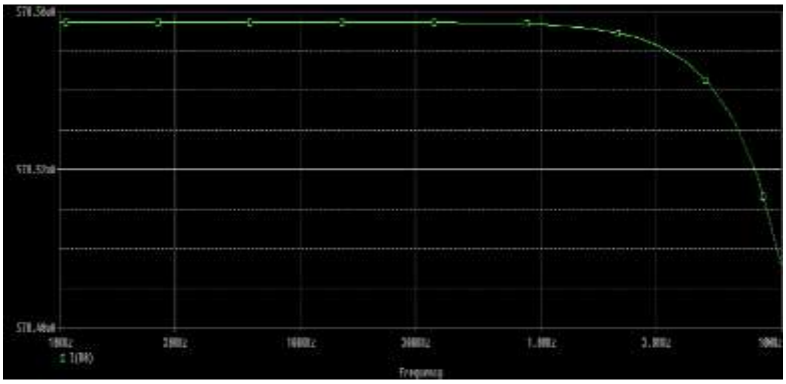

Fig.4. Magnitude of output current simulated in OrCAD and plotted against frequency, over 20Ω to 10kΩ load

The output impedance Z_o is evaluated in simulation by short-circuiting the input voltage V_1 and connecting a current source across the output of the VCCS circuit. The output impedance is then defined as the ratio between the voltage across the load R_L and current which flows into Z_o. It must be emphasized that in the simulations that, Z_o is independent of R_L. This is because non-linear properties of the OTA such as slew rate and maximum output voltage are not simulated. Fig. 5shows the magnitude of output impedance simulated over frequency range 10 kHz to 1MHz, which is 5.8MΩ up to 1MHz. These results meet requirements of EBM.

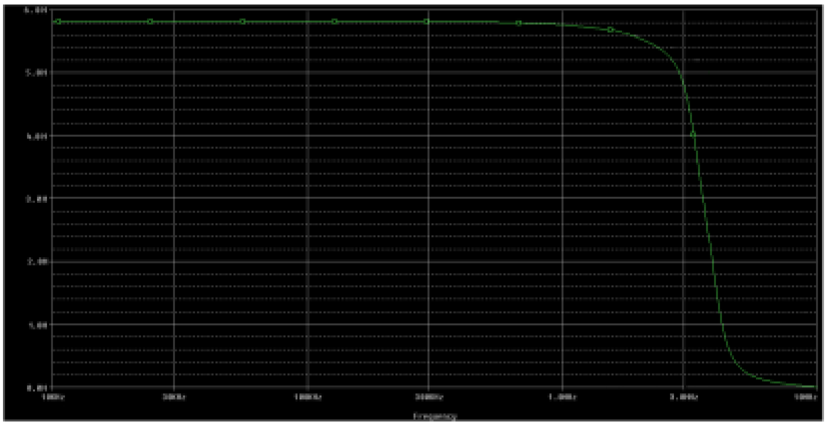

Fig.5 Output impedance of proposed current source from 10 kHz to 10MHz.

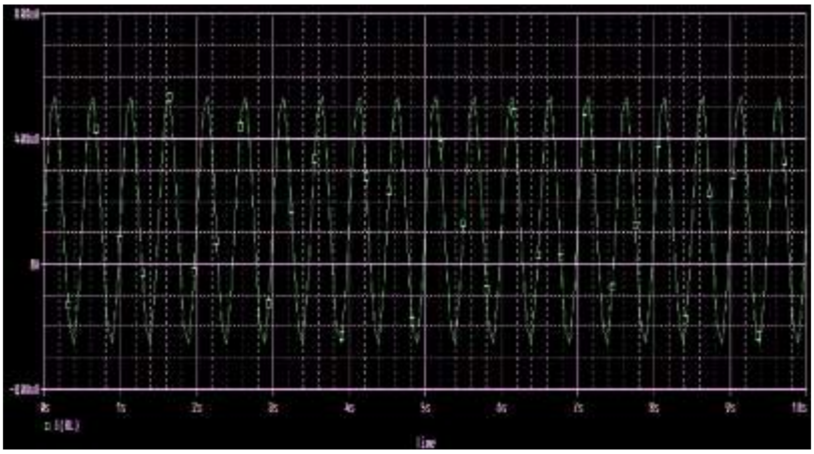

Fig.6 Output waveform of the proposed Howland current source

The output waveform of current source while driving 1kΩ is shown in Fig.6. The waveform is stable for the range of load impedance from 20Ω to 10kΩ.

III. COMPARISON

A comparison among different current sources simulated by [3] [5] [6] and proposed Howland current source is done on the basis of values of performance parameters shown by these circuits. It can be seen from

Table 1 that the proposed OTA based Howland current source has the best stability among the five current sources when frequency and load impedance changes. In Table 2 proposed model shows significant improvement in output impedance in comparison with improved Howland model.Power dissipation is one parameter that affects desired performance of a circuit. This parameter has not been calculated during simulation of most of the current source models considered here. But in [6] it is computed and peak power dissipated is 1.54mW for 2.43kΩ whereas for proposed model this comes out to be 7.20μW and this is significantly lesser, as shown in Table 3.

Table 1. Comparative performance analysis of different current sources

Current sources	Frequency range	Load impedance	Output current
Howland [5]	10 kHz – 500 kHz	0– 3 kΩ	8.932 mA
Dual op-amp [5]	10 kHz – 500 kHz	0– 3 kΩ	8.696 mA
Improved Howland [3]	10 kHz – 10 MHz	1 kΩ	2 mA
Proposed Howland	10 kHz – 10 MHz	20 Ω – 10 kΩ	578.56 µA

Table2. Output impedance parameter of current sources

Current source	Output impedance
Improved Howland [3]	3.3MΩ
Proposed Howland	5.8 MΩ

Table 3. Power dissipation parameter of current sources

Current source	Power dissipation
BasicHowland [6]	1.54mW
Proposed Howland	7.20µW

IV. CONCLUSION AND DISCUSSION

This work discusses and simulates the performance of OTA based Howland current source for use in Electrical Bio-impedance measurement (EBM).Simulation results of proposed Howland current source showing very improved results than others. Its output current is coming out to be 578.56 µA over frequency range of 10 kHz to 10MHz. Resulting output impedance is 5.8MΩ up to 1MHz. The output current and impedance of the circuits were investigated over the frequency range from 10 kHz to 10MHz for relatively large range of resistive loads (20Ω-10kΩ).

The fact that this type of current source circuit contains positive and negative feedback loops, resistor mismatch can also degrade the frequency response. Optimized improved Howland current sources with output impedance many times greater than the results shown in this work can be found in other research works but they suffer from instability problems due to non-idealities of the amplifier and imbalance of Howland circuits. Therefore, cannot be controlled. The proposed OTA based current source has been shown to have better performance for wide frequency range than all other current sources used in past research works.

Although the current source projected in this work simulated only in PSPICE, the results are encouraging for the implementation of real life circuits.These results are well above expectations and much better than other current sources used throughout the literature.The next step would be to use this proposed current source design in the electrical bio-impedance measurement system.

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