Mirrored Modified Howland Circuit for Bioimpedance Applications: Analytical Analysis

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Abstract. Multifrequency Electrical Bioimpedance (MEB) has been widely used as a non-invasive technique for characterizing tissues. Most MEB systems use wideband current sources for injecting current to load and instrumentation amplifiers for measuring the resultant potential. Current sources should present intrinsically high output impedance in a very wide frequency range. The objective of this work is to investigate the performance of the Mirrored Modified Howland Current Source (MMHCS) by comparing the analytical solution with the SPICE simulation. It was implemented four MMHCS circuits by using four different operational amplifiers each one. The output current was set to 1 mAp (peak) in the frequency from 1 Hz to 100 MHz. Both techniques presented similar results at lower frequencies. It can be concluded that the output impedance of the circuit is highly dependent of the open-loop gain of the operation amplifier. The analytical solution showed that it is possible to project a current source by using only theirs output current and impedance equations.

1. Introduction

Multifrequency Electrical Bioimpedance (MEB), also called Spectroscopy, has been widely used as a non-invasive technique for detecting cancerous tissues [1,2,3], tumors [4], meningitis [5] and brain cellular oedema [6], for analyzing body composition [7] and bovine milk quality [8]. The EIS is considered a fast, inexpensive, practical and efficient technique [9], which also can be found available for emerging wearable applications [10] and for on-chip systems such as the AD5933 [11].

Most EIS systems consist of applying a multi-frequency sinusoidal current of constant amplitude in the tissue sample, measuring the resulting potential and then calculating the transfer impedance (Zt) [9]. In order to get an accurate calculated transfer impedance, it is necessary to assure that the injecting current has a constant amplitude over a wide frequency range, which may be obtained by using a current source with high output impedance [12]. However, stray capacitances reduce the current amplitude at higher frequencies [13]. High performance current source with a wide bandwidth by using operational amplifiers has been widely developed [14,15]. Current sources in EIS may be based on the operational transconductance amplifier (OTA) approach [16,17], but they suffer from linearity and common mode voltage at the load. Most current sources in EIS use the modified Howland structure [18].

Our targeted measuring applications require an operating frequency band of 100 Hz to 1 MHz and current amplitudes of up to 1 mAp (peak). The objective of this work is to investigate the

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analytical solution of the output current and impedance from a modified Howland current source by considering the non-idealities of the operational amplifier. It also compares SPICE simulations to the analytical solution.

2. Materials and Method

2.1. Modeling of the modified Howland circuit

The modified Howland current source is shown in Figure 1. The gain is set by $R_5$, modified by the ratio of $R_1/R_2$ (which is typically 1/1). Consequently it can be used low values for $R_5$, and keep all the other resistors high in value, such as 100k or 1 MΩ. In this type of circuit, it can be noted that it is not just the ratio of $R_3/R_4$ that must match $R_1/R_2$, but it is also the ratio $R_5/(R_4+R_3)$ that must be equal to $R_1/R_2$. By doing an intuitive analysis as mentioned above, it can be found that if $R_1=R_2$, then $R_4$ will normally be $(R_3-R_5)$. Conversely, $R_3$ can be made a little higher, to get the gain to balance out. Usually it is put a potentiometer in series with $R_3$.

In order to get good Common Mode Rejection Ratio (CMRR) and high output impedance it is necessary to trim the resistors and choose FET inputs amplifiers. On the other hand, the non-ideal characteristics of the operational amplifiers (i.e., input impedance $Z_{in}$, output impedance $Z_o$ and open-loop gain $A$) reduce frequency bandwidth of both output current and impedance.

![Figure 1. Schematic diagram of the modified Howland current source with grounded load.](image)

The output current $I_{out}$, which is also called Norton current, is calculated by short-circuiting the output voltage $V_L$ of the circuit and grounding the input signal $V_{IN}$. The Norton current $I_{out}$ is shown in (1), where $R_1=R_2=R_4=R$, $R_5=r$ and $R_3=R+r$.

$$I_{out} = \frac{(2Z_{in}r-2 Z_o)r^2+(Z_{in}r-A-3 Z_o-r-2 Z_{in}Z_o)R-Z_o r-Z_{in}Z_o r}{4(r+Z_o)r^2+(2Z_{in} (2rA+4Z_o)+3r^2+ (6Z_o+4Z_{in})r)R^2+(Z_{in} r(rA+4Z_o)+2(Z_o + Z_{in})r^2)R+Z_{in}Z_o r^2}$$

(1)

On the other hand, the output impedance $Z_{out}$ can be calculated by short-circuiting the input $V_{IN}$ and adding a voltage source at the output of the circuit. The complete equation for $Z_{out}$ is shown in (2), where $R_1=R_2=R_4=R$, $R_3=r$, $R_5=R+r$ and $V_{IN}=0$.

$$\frac{1}{Z_{out}} = \frac{4r^3+(6r+4(Z_o+Z_{in}))r^2+(2r^2+4((Z_0+Z_{in})r+Z_0Z_{in})R+Z_0r(r+2Z_{in})}{4(r+Z_o)r^2+(Z_{in} (2rA+4Z_o)+3r^2+(6Z_o+4Z_{in})r)R^2+(2Z_o r^2+Z_{in} ((A+2)r^2+4Z_o r))R+Z_{in}Z_o r^2}$$

(2)
2.2. Mirrored Modified Howland Current Source (MMHCS)

A MMHCS circuit consists of two wide bandwidth operational amplifiers, as shown in Figure 2. The MMHCS is a voltage controlled current source with a floating load $R_{\text{load}}$ and it consists of two symmetrical modified Howland structures. Both output current and impedance were investigated by using the SPICE simulator. Four types of operational amplifiers were used in the simulations, as shown in Table 1. For simulations purpose, the circuit is set to supply an output current $\pm I_{\text{OUT}}$ of 1 mAp (peak) over the frequency range 1 Hz to 100 MHz, which is ideally controlled by the ratio between the input voltage $V_{\text{in}}$ ($V_1=V_2= 1 \, \text{Vp}$) and the resistor $r$ ($= 1 \, \text{k}\Omega$), where $R_1=R_2=R_4=R=100 \, \text{k}\Omega$, $R_5=r$ and $R_3=R+r$.

![Figure 2. Schematic diagram of the simulated mirrored modified Howland current source.](image)

The output impedance of this circuit is frequency dependent, as shown in (2). It was taken into account the non-ideal characteristics of the operational amplifier, such as: input impedance $Z_{\text{in}}$, output impedance $Z_0$, and the open-loop gain $A$ (see Table 1). The values from Table 1 are used to calculate the analytical solutions for both output current and impedance of the MMHCS circuit.

| | $Z_{\text{in}}(s)=R_{\text{in}}/(1+sR_{\text{in}}C_{\text{in}})$ | $A(s)=A_0/(1+s/\omega_{\text{c0}})$ |
|---|---|---|
| OPA655 | $1\, \text{G}$ | $1.2$ | $0.04$ | 58 | $400\pi \, \text{k}$ |
| TL081 | $1\, \text{G}$ | 0 | 10 | 105 | $50\pi$ |
| OP07 | $50\, \text{M}$ | 0 | 60 | 113 | $8\pi$ |
| uA741 | $2\, \text{M}$ | 1.4 | 75 | 97 | $30\pi$ |

Note. $A_0$ of the opamp has been extracted from the plots of the open loop gain versus frequency included in the datasheet.
3. Results

Both analytical and simulated results of the output current are showed in Figures 3(a) and 3(b), respectively. It can be seen that the output current keeps constant and equal to 1 mA up to approximately 100 kHz for both results. However, SPICE simulations have showed a wider frequency response for the operational amplifier OPA655. It can also be observed that the operational amplifier µA741 showed analytically the worst frequency response whereas OP07 in the SPICE simulations.

![Current frequency response of the MMHCS circuit, using a load of 1 kΩ. (a) Analytical solution. (b) SPICE simulation.](image)

The modulus of the output magnitude for both analytical and SPICE simulation are showed in Figures 4(a) and 4(b), respectively. It can be seen that the output impedance at very low frequency is approximately 200 MΩ when implementing the MMHCS with OP07. However, at 1 MHz, the operational amplifier OPA655 presented a better performance and showed an output impedance of approximately 100 kΩ.
In order to investigate the variation in the output of the MMHCS circuit due to loading effects, Figure 5 shows the linearity of the output current by varying the load values from zero (short-circuit) to 5 kΩ at 100 kHz. It can be observed that both OPA655 and TL081 present good linearity response. The maximum linearity error occurs for a 5 kΩ load and they are approximately 17% for the OP07 whereas 13% for the μA741.
4. Discussions
It was showed that the results from the analytical equations for both output current and impedance spectrum are very close to the SPICE simulations, especially at lower frequencies. Even the non-linear behavior of the operational amplifier OPA655 at high frequency presented in the simulations could be also observed in the analytical solutions.

The operational amplifier OP07 showed a difference between analytical equation and SPICE simulations for output current spectra, especially at higher frequencies. This might be explained by the fact that the SPICE simulator does take into account others non-idealities effects which are not considered in the analytical equations. The analytical equations were not taken into account the slew rate and the input common mode impedance of the operational amplifiers, for example. Furthermore, the simulator models a more realistic open loop gain of the amplifier, for example by considering a second-order relationship with frequency. Here the open-loop gain was considered to be a first-order function of frequency.

It has to be emphasized that the output current of the MMHCS circuit cross the load does depends on the output impedance of the circuit, as shown in Equation 3. The higher the output impedance of the circuit, more closely the load current would be to the output current projected in the circuit. Furthermore, it was not considered parasitic capacitive effects (i.e. stray capacitances from cables, electrodes, circuit layout, etc). Cautions should be considered when comparing SPICE simulation to real life circuit, as the presence of parasite capacitances can reduce the output impedance of the circuit, especially at higher frequencies.

\[
I_{\text{Load}} = \frac{I_{\text{out}} Z_{\text{out}}}{Z_{\text{out}} + R_{\text{Load}}}
\]  

(3)

If we consider the input impedance of the operational equals to infinity and its output impedance equals to zero, it can be calculated from (2) that the output impedance of the MMHSC is directly proportional to the open-loop gain of the opamp.
5. Conclusion
A comparison between the analytical solution for the output current and impedance of a MMHCS circuit and the SPICE simulation were performed. It can be concluded that it is possible to reproduce these results from simulations. These results may encourage the researches to simulate and project a MMHCS circuit by using only the analytical equations 1 and 2. Gain from these results might be important when projecting wide frequency bandwidth and high output impedance Howland modified current sources.

6. References

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