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MINIMIZATION OF STRAY CAPACITANCES IN HOWLAND CURRENT SOURCE

D. Bouchaala[1, 2], O. Kanoun[1] and N. Derbel[2]

[1]Technische Universität Chemnitz, Germany
[2]University of Sfax, Higher Engineering School of Sfax (ENIS)
dhouha.bouchaala@etit.tu-chemnitz.de

Abstract: Stray capacitances, due to e. g. limitations of layout and the use of active circuit elements, lead to limitations of the performance of bioimpedance devices at higher frequencies. The effects of stray capacitances can be avoided by several methods, such as Generalized Impedance Converter (GIC), Negative Impedance Converter (NIC) or external compensating operational amplifier.

In this work, the investigation of NIC and GIC for Howland current source shows that both methods are not suitable for multifrequency measurement system, because they need different adjustments of components for every frequency. The external compensation method is investigated with uncompensated and compensated operational amplifier. Simulation results show that the addition of compensation capacitor externally to the operational amplifier in Howland current source has good accuracy about 0.02 % at high frequencies up to 1MHz.

Keywords: Stray capacitance, bioimpedance spectroscopy, voltage controlled current source, Howland topology, compensation capacitor.

1. INTRODUCTION

Bioimpedance spectroscopy has several potential applications in medicine e.g ischemia, lung edema and skin cancer. Bioimpedance measurement devices using current excitation have advantages because they can easily maintain the medical requirements concerning current limitation without knowledge about the biological material under test.

The current excitation source performance is decisive for the system performance of bioimpedance devices. The technical features required for accurate current source for bioimpedance measurement system are high output impedance, stable magnitude of the injected current lower than 0.5 mA [1] through a wide range of frequency between 5 kHz and 1 MHz [2]. A wide frequency range is very important in general to be able to separate different effects appearing in the impedance spectrum. The frequency range in the neighbourhood of 1 MHz, corresponding to the β-dispersion [3, 4], is very important especially for characterizing effect at the cell level, such as for differentiation between normal and pathological tissues. The realization of suitable current sources for this relative high frequency is a challenging task.

Different designs of current source have been studied in literature, such as current conveyors [5], current mirrors [6], transconductance amplifiers [7], Howland topologies [8] and load-in-the loop current sources [9]. In recent years, the Howland topology has been becoming more and more popular in bioimpedance measurement as it combines both simplicity and high performance. Most of current sources fulfil the requirements at low frequencies, but their performance degrades due to the presence of stray capacitances, at high frequencies from 300 kHz to 1 MHz.

The aim of this paper is to study methods eliminating the influence of stray capacitances especially at high frequencies. This is to improve the stability of the output current at high frequencies up to 1 MHz. In section 2, Howland current source structure and its design are analyzed. In section 3, stray capacitances causes and methods for their minimization are explained. In the last section, the proposed new current source including minimization of stray capacitances is described with details.

2. HOWLAND CURRENT SOURCE

The Howland current source can have single or dual configurations. The single configuration represents the basic Howland topology and uses a single operational amplifier with both negative and positive feedback (Fig.1).

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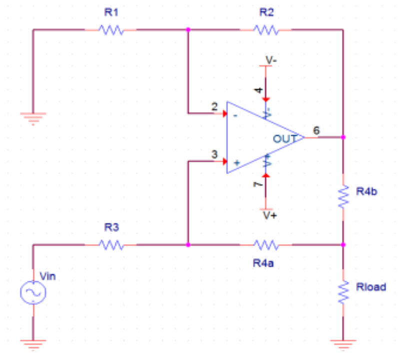

Fig.1: Basic Howland current source

Both feedbacks lead to the advantage, that the output resistance can be easily adjusted. But they may lead also simultaneously to oscillations at high frequencies limiting the frequency range of the current source.

In dual configuration, a second amplifier is added, in one of feedback paths of first operational amplifier, increasing the circuit's output impedance and maintaining high accuracy at high frequencies. Also, it reduces errors that the first operational amplifier produces.

In [10], we have shown that the enhanced Howland current source with voltage follower in negative feedback has excellent accuracy at high frequencies in comparison to other Howland topologies.

Furthermore, the choice of operational amplifier and circuit parameters is very important to ensure a voltage controlled current source with high output impedance. High accuracy and stability requires tight matching resistors and high common mode rejection ratio of the operational amplifier.

2.1. Amplifier characteristics

For accurate current source, important requirements for the amplifier [11] are summarized in Table II:

Table II: Requirements for Operational Amplifier

Amplifier Characteristics for Performant Current Source			
Very low	Less than	High	More than
Offset voltage	100 µV	CMRR	100 dB
Offset drift	5 µV/ºC	PSRR	100 dB
Input bias current	50 nA	Loop gain	100 dB
Offset current drift	100 pA/ºC		
Noise	10 nV/√Hz		

Most of the amplifier characteristics are dependent on the input offset voltage which is the differential input voltage between the operational amplifier's two input terminals. In fact, input offset voltage drift, common mode rejection ratio (CMRR), power supply rejection ratio (PSRR) are the ratio of change in input offset voltage to respectively the change in respectively measured temperature, input common mode voltage and level of power supply that produces it.

For a high precision current source generating micro amps, a very high performance precision operational amplifier is recommended with low offset voltage and input bias current [11], which is the average of currents into the operational amplifier's two inputs, when the output is at zero volts and with no load.

For applications in portable bioimpedance devices, it is very important to focus on amplifiers having low noise, high bandwidth and low power consumption, such as the operational amplifier described in Table III.

Table III: Characteristics of Selected Amplifier

Amplifier	Offset Voltage (µV)	Offset Voltage Drift (µV/ºC)	Input Bias current (µA)	Offset current drift (nA/ºC)	Quiescent current (mA)	Input Voltage Noise (nV/√Hz)	CMRR (dB)	PSRR (dB)	Loop Gain (dB)
AD8021	400	0.5	7,5	10	7,7	2,1	98	95	76
AD8041	2000	10	1,2	200	5,8	16	80	80	99
AD8055	3000	6	1,2	400	5,4	6	82	72	71
LMH6655	1000	6	5	300		4,5	90	76	20

From Table III, AD8021 is selected for its low offset voltage, low offset voltage drift, low input voltage noise density, high CMRR and high PSRR. High common mode rejection ratio leads to high output impedance for current source.

2.2. Resistor Specifications

In the design of Howland current source, the closely resistor matching and the imperfect resistor balancing in practice remains a fundamental problem.

Using one or two additional precision resistors in series with the main resistor [11] and the resistor's percentage tolerance less than 0.1 % provides a good performance, lowest drift and circuit accuracy.

3. ELIMINATION OF STARY CAPACITANCES

In real implementation, at relative high frequencies by 1 MHz, the performance of voltage controlled current source is limited by the stray capacitance effect. There are some methods, such as Generalized Impedance Converters (GIC), Negative Impedance Converters (NIC) and externally compensated operational amplifier to avoid or minimize the influence of parasitic capacitance.

3.1. Generalized Impedance Converter (GIC)

The GIC contains two operational amplifiers and five adjustable impedances. The output of the Generalized Impedance Converter [12] is the following:

$$Z_{GIC} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$$

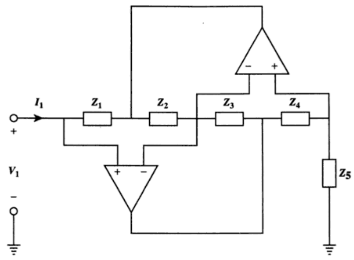

Fig.2: Generalized impedance converter circuit [12]

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Depending on the components choice at the position 1 to 5, the Generalized Impedance converter can have many outputs, such as:

- Frequency-dependent-negative resistance

$$Z_{GIC} = -\frac{R_3}{C_1 C_5 R_2 R_4 \omega^2}$$

- Inductive behavior

$$Z_{GIC} = \frac{R_1 R_3 R_5 j\omega C_2}{R_4} = j\omega L$$

In this work, we choose the structure generating inductance because its performance at high frequencies [13].

An inductive behaviour can be realized using the topology given in Fig.2:

$$L = \frac{R_1 R_3 R_5 C_4}{R_2}$$

In Norton equivalent circuit of real current source (Fig.3), the output current is associated with the output resistance, stray capacitance and inductance synthesised by GIC.

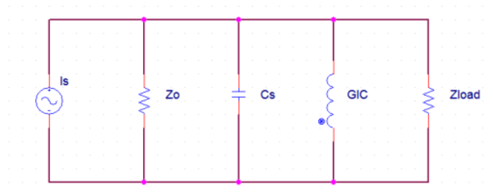

Fig.3: Norton equivalent circuit of real current source connected to GIC

When the imaginary part of parallel impedance is set to zero, the stray capacitance effects are completely cancelled.

$$Im\,(Z) = j\omega L + \frac{1}{j\omega C}$$

This condition can be fulfilled at:

$$\omega = \frac{1}{\sqrt{LC}}$$

For multifrequency system, the inductance L must be adjusted at every frequency to fulfil the condition. To adjust the inductance, five resistors should be adjusted in the case of GIC. This is why; this method is difficult to apply to cancel the stray capacitances.

3.2. Negative Impedance Converter (NIC)

The NIC [14] realizes in general negative impedances. The topologies of Negative Impedance Converter (NIC) are:

- Negative resistance converter

$$Z_{NCC} = -R$$

- Negative capacitance converter

$$Z_{NCC} = -\frac{1}{j\omega C}$$

- Negative inductance converter

$$Z_{NCC} = -j\omega C R^2 = -j\omega L$$

The main interest in this work is to cancel the stray capacitance. Therefore, we focus on the Negative Capacitance Converter (NCC). NCC contains an amplifier, capacitance and two resistances (Fig.4).

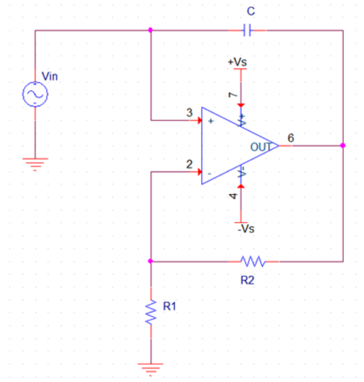

Fig.4: Negative capacitance converter circuit

The current through R_1 is:

$$I_{R_1} = \frac{V_{in}}{R_1}$$

The output voltage of the amplifier at the pin 6 is:

$$V_6 = V_{in} + I_{R_1} R_2 = \left(1 + \frac{R_2}{R_1}\right) \cdot V_{in}$$

The current flowing through the capacitance is:

$$I_{in} = \frac{V_{in} - V_6}{Z_C} = -\frac{R_2}{R_1} \cdot \frac{V_{in}}{Z_C}$$

Then, the impedance is the following:

$$Z_{NCC} = \frac{V_{in}}{I_{in}} = -\frac{R_1}{R_2} \cdot Z_C$$

When the condition $R_1 = R_2$ is fulfilled:

$$Z_{NCC} = -Z_C$$

In Norton equivalent circuit (Fig.5), the output current is associated with the output resistance, stray capacitance and capacitance synthesized by NCC.

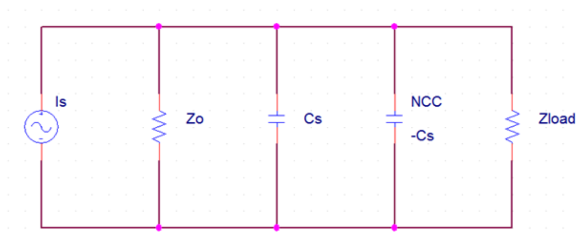

Fig.5: Norton equivalent circuit of real current source connected to NCC

When NCC capacitance is equal to stray capacitance, the imaginary part of the parallel impedance is zero.

$$Im(Z) = \frac{1}{j\omega C} - \frac{1}{j\omega\,C} = 0$$

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This method is not suitable for multifrequency measurement system, because it needs adjustment of components for every frequency.

3.3. External compensation

Externally compensating operational amplifiers [15] reduce the effects of stray capacitance at the output; increase the gain bandwidth and the slew rate. The adjustable feedback capacitor compensation reduces the noise and provides a flat amplitude response, thereby increasing the performance of current source.

In [16], external compensating operational amplifier AD8021 is used in basic Howland current source. In this work, we choose this amplifier for dual configuration Howland circuit in negative feedback which has good accuracy than the single configuration [10]. AD8021 is also compared with uncompensated amplifier AD8041.

4. SIMULATION ANALYSIS

Different values of the compensation capacitor, Cc, were used, in order to find the optimum configuration with lowest error.

Table IV: Simulation results with different resistor configurations

	R_1	R_2	R_3	R_{4a}	R_{4b}	Cc	Error 1kHz	Error 1MHz	Flatness
AD8041	9k	2k	9k	1k	1k		0.006%	0.274%	0.313%
	6k	3k	6k	1k	2k		0.007%	0.221%	0.27%
	5k	2.5k	5k	0.5k	2k		0.007%	0.195%	0.24%
AD8021	9k	2k	9k	1k	1k	1pF	0.016%	0.028%	0.049%
	6k	3k	6k	1k	2k	10pF	0.02%	0.141%	0.189%
	6k	3k	6k	1k	2k	3pF	0.02%	0.049%	0.079%
	6k	3k	6k	1k	2k	1pF	0.02%	0.022%	0.048%
	5k	2.5k	5k	0.5k	2k	1pF	0.021%	0.017%	0.043%

Table IV shows that errors at low frequencies are smaller than errors at high frequencies. Comparing between two amplifiers, the uncompensated operational amplifier AD8041 has the biggest error at 1 MHz and biggest flatness.

The external compensated operational amplifier AD8021 has the best performance, not only the errors at 1 MHz, but also the worst flatness. This is because of the high output impedance obtained by the addition of a voltage follower in the negative feedback and also because of the addition of compensated capacitor to the amplifier.

In addition, from table IV, we see that the higher the compensation capacitance, the higher the error at 1 MHz and the flatness. The best configuration for lowest error at 1 MHz and lowest flatness is: R_1=5 KΩ, R_2=2.5 KΩ, R_3=5 KΩ, R_4=0.5 KΩ, R_5=2 KΩ and C_C = 1pF.

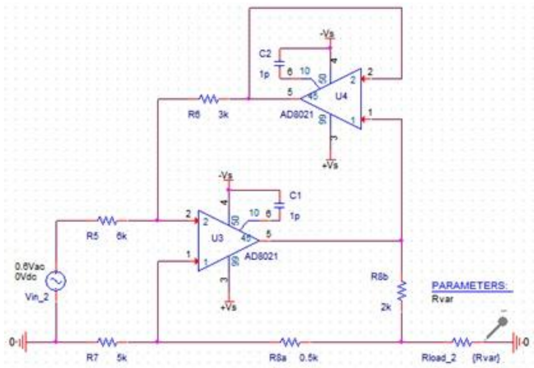

Fig.6: Enhanced Howland current source with voltage follower in negative feedback using AD8021

In conclusion, the Enhanced Howland circuit in dual configuration with negative feedback using an external compensated operational amplifier AD8021 (Fig.6) has accomplished the higher accuracy at higher frequencies. For this reason, it is selected to be implemented and tested on board.

5. CONCLUSION

The dual configuration of Howland current source in negative feedback offers the best solution as it combines high performance and simplicity. The performance of Howland circuit is related to the performance of chosen operational amplifiers. The resistor are required to be closely matching and the operational amplifier is chosen with high common mode rejection ratio, low input bias current and low input noise voltage density.

At high frequencies, the main limitation is the presence of stray capacitances. Among many solutions to cancel their effects, the addition of external compensation capacitor shows a good performance at high frequencies until 1 MHz in simulation results.

At low frequencies, compensated operational amplifier AD8021 has slightly larger errors than uncompensated operational amplifier AD8041. Instead of that for high frequencies up to 1 MHz, AD8021 has smaller errors around 0.02 % than 0.2 % for AD8041. In addition, the flatness for the compensated amplifier (0.05%) is smaller than the uncompensated one (0.2%). Thereby, the external compensated operational amplifier AD8021 has the best performance, not only the errors at 1 MHz, but also the worst flatness.

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