Mirrored improved Howland Current Source with Wien Bridge-Based Oscillator

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***Abstract*—Regarding electrical bioimpedance applications in medical areas such as: physiology, nutrition and disease diagnosis, oscillators and current sources are crucial to the development of hardware solutions. Using a Wien brigde oscillator as a voltage power supply for a mirrored improved Howland current source, the proposed circuit provides a high accurate current output for a certain range of impedance values, which for any human subject can be modeled as a a resistor in series with a capacitor. The oscillator consists of an amplifier and a bandpass filter generating sinusoidal waves specially designed to provide a low power signal with a frequency of 50kHz. The high transconductance of the designed current source allows the conversion of most part of the received voltage signal into a current supply output. As a mechanism of support to simulate the proposed circuit, the softwares Multisim and LTSPICE were used. The resulting graphs were plotted with the aid of Matlab R2016a. Finally, a prototype was build using integrated circuits, capacitors and resistors. Considering the demand for such simple and cheap components, the proposed hardware presents as a very viable solution for other medical applications.**

***Index Terms*—Oscillators, Current Sources, Bioimpedance Analysis, Tranconductance, Stability.**

I. Introduction

OSCILLATORS are integrated electronics circuits that are able to produce periodic alternating current signals using a DC power supply.

There are several types of signals that can be produced changing the waveform and frequency according to the circuit, for instance, sine waves, square waves, sawtooth waves and triangular waves. There are different types of oscillators as Wien, Armstrong , Hartley , Colpitts, Multi-Wave. Wien receives a constant function and returns a sinusoidal function.

Oscillators have many appliances in our daily life, such as radio waves, in tone generators - games, electrical instruments, the robot R2D2 from Star Wars; clock signals that control the digital processors speed (computers processor); chronometers (generating counters to keep track in time); treatment of the cancer; radio and mobile communications (it is used to generate the sinusoidal output signals with a very high frequency).

In addition, medical equipments already uses oscillators to converts direct current into alternating current. However they are not only expensive but they are difficult to debugging. In other words it is not easy to find an error or replace some component of that kind of equipment. Then the Howland circuit can replace it with a low cost and easy to relieve to. It is composed by the Wien Bridge oscillator, a buffer and the Howland circuit wich all of them are shown in sections II, III, IV and V, respectively.

This paper is divided into five sections, including this introduction. In Section II, this paper describes how the direct current is going to be tranformed into, modeling the Wien Bridge oscillator. In Section III the paper describes the circuit responsible for providing the controlled current whatever the source connected to the circuit. In other words, it is the Howland circuit oscillator's description. The Section IV shows the circuit that gives power to the system, being able to take the output signal in a sensor, for example. Section V is the simulation section which shows the circuit characteristics and response for each load connected to it. In Section VI is possible to see all the experimental results similarities with the simulation. Section VII, in this paper, explains the results gotten after performing the simulation and experimental proposed.

II. The Wien's Bridge

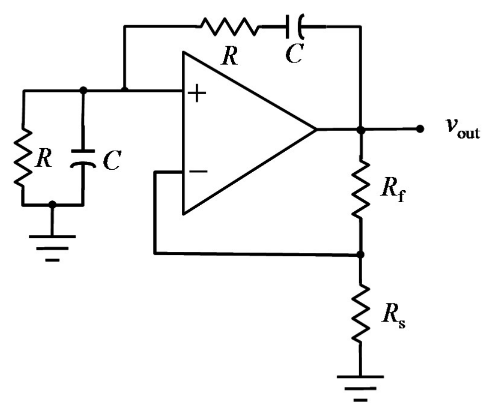

Fig. 1. Wien bridge.

The Wien bridge oscillator is a specific type of electronic oscillator. It was developed by Max Wien in 1891 to measurement of impedances, but this is not the only utility of this circuit, nowadays it is also used to measure the audio frequency. it is based on the bridge circuit in figure (1). The Wiens circuit can generate sine waves with a large range of frequencies, it has high quality of resonant frequency, low distortion, and also in the tuning. Our circuit will be designed to satisfy the 50kHz frequency only.

The oscillator can be divided in two parts: an amplifier with positive gain and a bandpass filter. The filter has a resistor (R_1) in series to a capacitor (C_1) and a resistor in parallel

(R_2). If $R_1 = R_2 = R$ and $C_1 = C_2 = C$, the frequency of oscillation (in Hertz) is given by:

$$f = \frac{1}{2\pi RC} \tag{1}$$

Connected to the negative input of the amplifier there are two resistor R_a and R_b. The condition to the oscillator circuit generate a stable oscillation is given by:

$$Rf = 2RL \tag{2}$$

Due to the ideal model, the voltage at the amplifier's terminal is given by $V_+ = V_-$. Therefore, the direct gain is calculated by:

$$A(jw) = 1 + \frac{R_b}{R_a} \tag{3}$$

So, the V+ is:

$$V_+ = \frac{V_o utput \frac{R}{1+jwRC}}{R + \frac{1}{jwC} + \frac{R}{1+jwRC}} \tag{4}$$

According to Barkhausen criterion, which determines that the transfer function modulus is equal to 1 and the phase is zero, we can find the relation between Rb and Ra and the oscillation frequency.

III. The Howland Circuit

The second oscillator configuration is the Howland (in figure (4) circuit which is a voltage-controlled current source that delivers a constant load current to an arbitrary load and it is independent of that load.

Howland circuits have been widely used in medical and also in industry applications such as neural stimulation, functional electrical stimulation, tissue characterization [1] , single-electrode capacitive sensors, bioimpedance measurement and electrical impedance tomography (EIT). They are used as source for exciting tissue over a wide frequency range. The simplicity, stability and high precision delivery of alternating current to biological loads make this type of device really useful.

In this article, it was designed the circuit to produce a current that is function of the input voltage with a frequency of 50kHz and the resistors of the circuit. It is based on an amplifier connected to four resistors with a resistance of R (ohms), with a negative feedback.

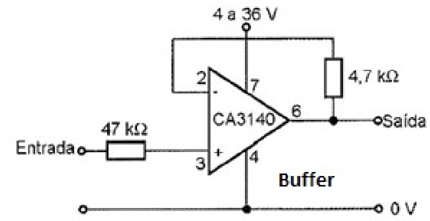

Fig. 2. Buffer.

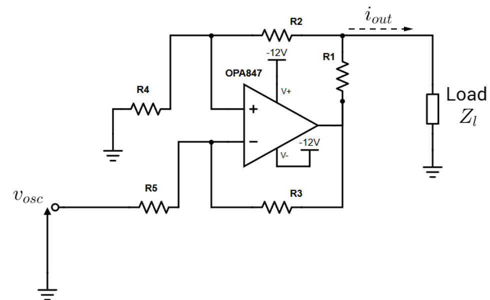

Fig. 3. Howland circuit.

The load current of the circuit in figure (2) is given by:

$$I_l = \frac{V_i}{R} \tag{5}$$

The Howland current pump is a voltage controlled current source (VCCS) that delivers a constant current output to an arbitrary load regardless of its impedance. The circuit is shown in Figure (2).

When its feedback paths are balanced, the Howland can be modeled as a linear VCCS [1]. The feedback paths of the circuit are balanced when the resistors are matched according to: [1][2].

$$\frac{R_4}{R_5} = \frac{R_2 + R_1}{R_3} \tag{6}$$

For an ideal approach the output current does not depend on the load, but it depends on the function of the input voltage and the value of the resistors.

A. Mirrored Howland circuit

The Mirrored Howland Source is a modified configuration of the Howland Current Source.It's formed by two single-ended Howland Circuits with the output conected to the load and that are feeded by two input voltages with 180 degrees phase shift.The two circuits share the same reference, what increase the stability of output current.This topology also eliminates the problem of grounding the load, which can bring some problems if aren't done correctly.A schematic of a Mirrored Howland can be seen in Figure 4.

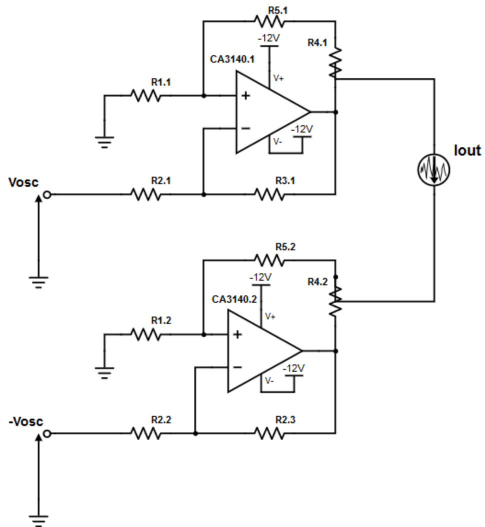

Fig. 4. Mirrored Howland circuit.

IV. BUFFER

To provide the power necessary to analyze the signal, it will be used a circuit compound by an operational amplifier which is the Buffer amplifier in figure(2). It is used to provide electrical impedance transformation from one circuit to another. The main characteristic of the circuit is that it does not change the voltage or current magnitude that the load may produce.

There are two main types of buffer: the voltage buffer and the current buffer. So, it will be connected to the Wien's circuit output to the input to the Howlland's circuit because it amplifies the power, that is too weak, at the output of the Wien's circuit. Moreover it also eliminates the output resistance of the Wien Bridge.

V. SIMULATIONS

Using the software LTspice, the figure (1) simulated according to the Wien's bridge specifications and its output was plotted. So R_1 = R_2 = R_a = R = $10k\Omega$, C_1 = C_2 = C = $10\eta F$, and R_b = $20k\Omega$. Therefore, after the simulation, the output wave form is shown in figure (6). It is in accordance with what was expected once that it converts the direct current in alternating current with a specif frequency (50kHz).

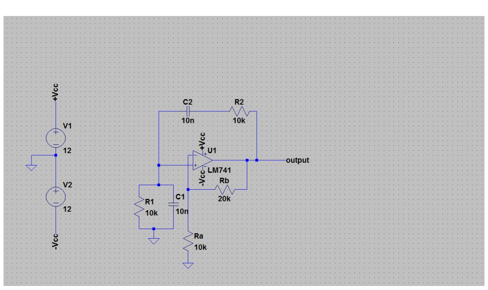

Fig. 5. Simulated Wien's bridge circuit schematic.

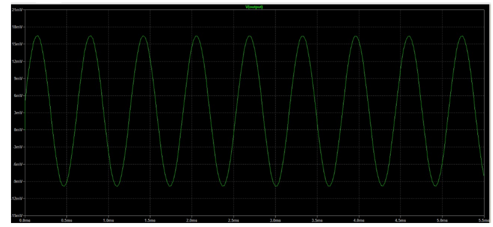

Fig. 6. Wien bridge output voltage simulation.

How it is perceptible the output is a micro ampere current (μA). Due to that the buffer's use is required to amplify the signal and give power to the system.

A. Howland

Connected to the buffer, the Howland circuit which is a Wheatstone bridge with and opamp (operational amplifier) in the middle of the bridge. The patient is connected to the circuit in the opamp's output because the opamp is in short circuit and its provide a controlled current to that node.

The figure (7) is the Howland simulated circuit where R_5 = R_6 = R_7 = R_8 = $1k\Omega$. This resistors compose the Wheatstone bridge putting the opamp in short circuit. The R_load resistor is the patient and whatever the load is the outcome is the same.

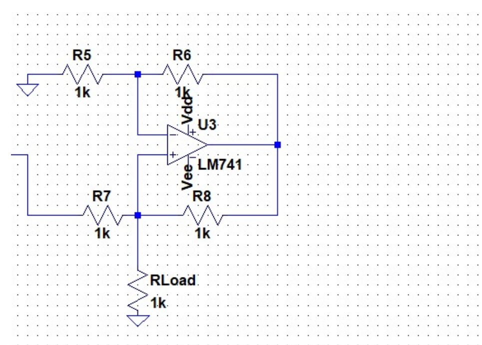

Fig. 7. Howland simulated circuit schematic.

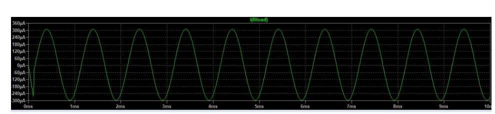

Fig. 8. Howland simulated circuit schematic with $R_load = 1k\Omega$.

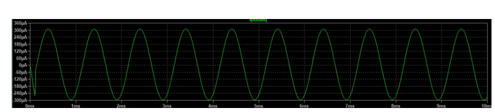

Fig. 9. Howland simulated circuit schematic with $R_load = 2k\Omega$.

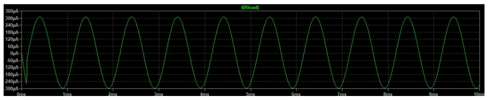

Fig. 10. Howland simulated circuit schematic with $R_load = 3k\Omega$.

As expected, the figures (8), (9) and (10) shown that the output does not change whatever the R_load is. In other words, the results got at the node is independent of the R_load. Thus, the current provided to the patient is controlled and under the safety limit requirement which is $30mA$. So it does not put the patient in danger.

The human body can be modeled as a capacitor of $100pF$ in series with a resistor with range of 1kΩ to 3kΩ what can be noticed in the simulation. The voltage and the current decreases for resistors greater than 3kΩ.

The outcome represented by (8), (9) and (10), is shown below, which the first part consists in the Wien Bridge - the first operational amplifier. The second one is the Buffer circuit - the second operational amplifier. Then, the Howland is connected to the Buffer's output.

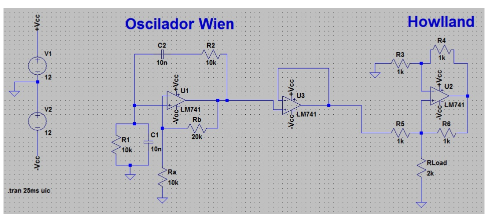

Fig. 11. Completed circuit simulation.

B. Mirrored Howland

In the simulations with the Mirrored Howland Source, the output current was measured in three different loads connected to the circuit. As it is perceptible in the figures (13) and (14), the output current is approximately constant, with a small variation of 3 μA. In these figures, the resistance of the load is respectively of 1 kΩ and 3 kOhm. When it is used a bigger load resistance, the output current changes more significantly than it did with the previous resistances. In this case, as can be seen in figure (15), the current signal has a peak in a lower level.

This results match with the expected characteristics of Mirrored Howland. To the objectives previously mentioned,the resistances only varies from 1 kΩ to 3 kΩ which is good enough to the medical circuits application within the range of Mirrored Howland circuit used.

A schematic of Mirrored Howland's circuit is depicted in figure (12) whose circuit is very similar to the Howland circuit. The main difference is that the patient - load - is connected between the two Howlands. Because of that there is no need to connect the load to the ground such as in Howland circuit.

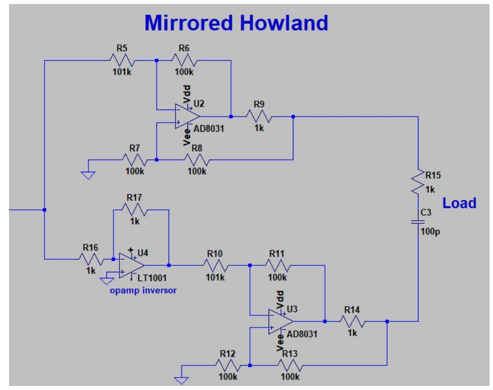

Fig. 12. Mirrored Howland's schematic simulation.

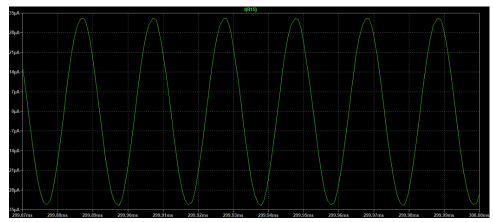

Fig. 13. Mirrored Howland's output for 1kΩ .

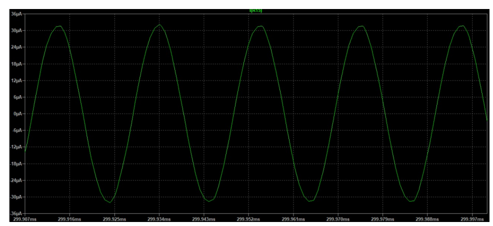

Fig. 14. Mirrored Howland's output for 3kΩ .

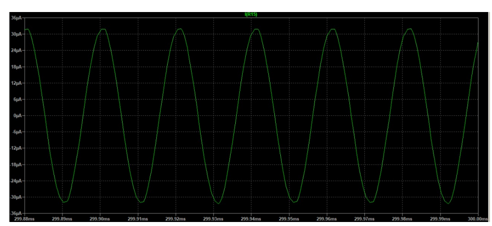

Fig. 15. Mirrored Howland's output for 6kΩ .

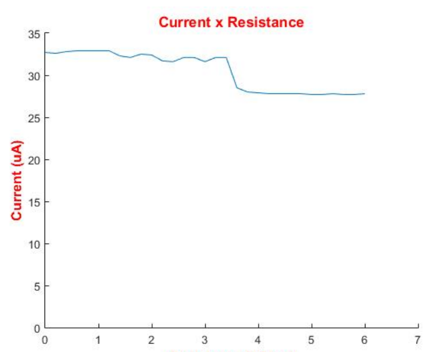

Fig. 16. Mirrored Howland's output plotted in Matlab.

The graph shown in figure (16) was plotted in Matlab and represents the relationship between the resistance of the load and the current that goes through it. It was taken values of resistance from 200 Ω until 6 kΩ, with steps of 200 Ω, and its respective current.As can be seen, the graphic is according to the expected results.The value of current decreases significantly after the resistance get higher than 3 kΩ.To values above 3 kΩ until 6 kΩ, the current stays constant, but have a lower magnitude.

VI. Circuit Implementation

Following the Figures (4), (6), (7) and (11) which is the completed circuit, it is possible to implement the circuit. Taking the Wien output data from oscilloscope and plotting in Mat Lab, it was possible to compare the input to the output waveform in figure (17). The blue sinusoidal wave is the ideal one produced by a function generator. The red sinusoidal wave is the one produced by the Wien circuit which converts direct current into alternating current.

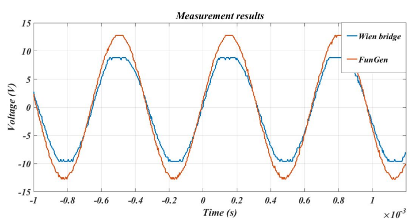

Fig. 17. Wien output X input plot.

The blue wave form is buffered once the operational amplifier (LM748) used to the Wien Bridge is not ideal. Comparing the Wien output int figure (17) to the voltage plot in figure (6), the values are close one to another considering the discrepancies.

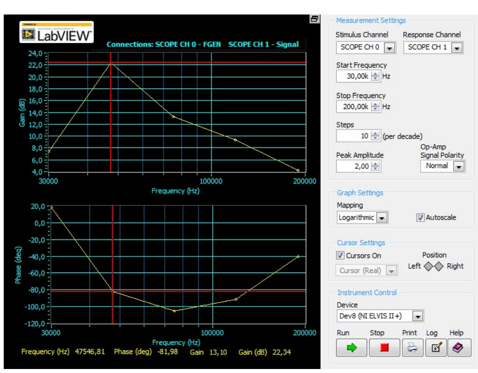

Fig. 18. Bode Plot.

Finally, using NI ELVIS II+ platform, in the bode section, is possible to get the Bode plot of the corresponding circuit. Connecting the wires properly at the input and output node and configuring the platform, it is possible to get figure (18) which shows the cutoff frequency at 47.546 kHz. Thereby, the current necessary to the medical procedures is taken only at that frequency.

VII. Conclusion

The Howland circuit is used in medical apparatus so it's accuracy and it's precision is extremely important. So the simulation and the experiment's results are compatible with few discrepancy. The operating frequency at the simulation is 50kHz and the experimental is 47.546kHz as it is shown in figure (18). This difference is caused by the non ideal components used in the experiment which have 10% of tolerance.

Nonetheless, the controlled current which is invariable to the Z_load connected to the circuit is $0.3mA$ in the simulation's outcome. Comparing to the experiment circuit - in table 1 - whose current was $0.36mA$,the discrepancy is not so significant once that the limit current is $30mA$.

TABLE I
Howland output table

	Theoretical results expected	Simulation	Experimental
Frequency (kHz)	50	50	47.546
Voltage (mV)	20	16	20
Current((μA))	300	320	363

As can be noticed from figure (18), the gain occurs at the 47.546kHz which produces the required current for the medical equipment. In addition, this gain does not change whatever the R_load connected to the circuit that simulates the human body impedance (C = $100pF$ and R_load range varies to $1k\Omega$ to $3k\Omega$). Connecting a greater resistance to the circuit, the gain decreases as shown in figure (16). In other words, the output current decreases and the equipment does not work properly.

On the other hand, the Howland circuit is not the most efficient circuit to this application once the patient must be connect to the same ground as It. Therefore, the Mirrored Howland circuit solves that problem. It works with one Howland lagged $180°$ to the other. That fact causes the current stability according to the figure (16) for load $1k\Omega$ to $3k\Omega$.

In conclusion, based on the simulation and the experimental results the outcome is satisfactory. Considering the money spend on this project, which was 22 reais - resistors, capacitors, integrated circuits, jumpers and protoboard, it is possible to replace the modern medical circuit system mentioned before to the Howland circuit or to Mirrored Howland circuit which is a little more expensive but it gives precise current outcome.

Appendix A
Wien Equation

In order to have a better comprehension of the Wien Bridge circuit, in this section we are going to find the frequency equation and the relation between Rf and R1. To get these equations we need to use the Barkhausen stability criterion, they are:

Transfer function modulus:

$|L(s)| = 1$, so $L(s) = A\beta$

-A is the gain;
- β is the reverse gain ($\frac{1}{A}$).

Transfer function phase:

$\phi = 0$

C_p, R_p, C_s and R_s are the components that will determine the oscillation frequency. Lets call Z_p the impedance in parallel of C_p and R_p and Z_s the impedance in serie of C_s and R_s. After doing it, lets find the reverse gain equation using the voltage divider:

$$V_a = \frac{VoutputZ_p}{Z_p+Z_s}$$

Therefore,

$$\beta = \frac{Z_p}{Z_p+Z_s}$$

$$A = \frac{Z_p+Z_s}{Z_p} = 1 + \frac{R_b}{R_a}$$

Owing to the frequency analysis, it will be applied to the circuit the LaPlace transformation. Hence, it is will be taken the letter s according to his definition as $s = \sigma + jw$. After all, Z_p and Z_s are:

$$Z_p = R_p // \frac{1}{jwC_p} = \frac{R_p}{sC_pR_p+1}$$

$$Z_s = R_s + \frac{1}{sR_s} = \frac{sR_sC_s+1}{sR_sC_s}$$

Substituting Z_p and Z_s in the gain (A) and reverse gain (β) expressions and with some arithmetics manipulation,(A) and (β) are:

$$\beta = \frac{1}{3+SCR+\frac{1}{SCR}}$$

Thus,

$$\phi = arctg(\frac{Im[\beta]}{Re[\beta]})$$

Consequently, the $Im[\beta]$ must be equal to zero to satisfy the Barkhausen criterion. Finally, the R_B and R_a proportion is:

$$L(s) = a\beta = \frac{1+\frac{R_b}{R_a}}{3+0+0} = 1$$

$$\frac{R_b}{R_a} = 2$$

To satisfy the stability criterion, the LaPlace variable must be purely imaginary $(s = 0 + jw)$. Then, the voltage gain will be expressed by:

$$L(s) = A\beta = \frac{1+\frac{R_b}{R_a}}{3+SCR+\frac{1}{SCR}}$$

The imaginary part of that expression must be equal zero. Hence,

$$SCR + \frac{1}{SCR} = 0$$

$$(SCR)^2 + 1 = 0$$

$$(wCR)^2 = 1$$

$$w = \frac{1}{CR}$$

$$f = \frac{1}{2\pi RC}$$

References

[1]
- Video used to the simulation analysis: ***Link***;
- ***Link***;
- ***Link***;
- ***Link***;
- ***Link***;

For more information, access:
- ***Link***.