Design and characterization of a multi-frequency bioimpedance measurement prototype

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Abstract. A multi-frequency bioimpedance measurement prototype is proposed, validated and characterized. It consists of an Improved Howland Current Source controlled by voltage, a load voltage sensing scheme through a discrete 3-opamp instrumentation amplifier, a phase and quadrature demodulation setup through analog multipliers, and digitization and processing of the signals using a digital benchtop multimeter. The electrical characterization of the measurement channel was done for resistive loads only, on four different circuits. Measurements were made on 10 frequencies, from 100 kHz to 1 MHz, with 10 load resistances, from 100 Ω to 1 kΩ, to obtain linearity, absolute error and frequency response. The best performance among the four circuits was a maximum absolute error of 5.55 %, and -1.93 % of load current variation at the worst case scenario.

1. Introduction
Many papers have already discussed the difficulties regarding the instrumentation used in bioimpedance analysis and electrical impedance tomography, like the studies of [7], [4] and [3], just to mention a few. Also, special attention was given to current sources, as in the works of [5], [8], [9], [11] and [10]. The present paper builds upon and intends to contribute to the knowledge of the afore mentioned works by detailing the design, implementation and characterization of a multi-frequency bioimpedance measurement prototype. It starts with the proposed measurement channel, followed by a description of each implemented block and a brief discussion on the printed circuit boards used. Then, its functioning is shown through waveforms measured at specific points. A methodology is proposed for characterizing linearity, absolute error and frequency response of the whole channel, as well as output impedance of the current source. In the end, a thorough discussion of the results is presented, concluding the paper with future works and possibilities.

2. Proposed measurement channel
The block diagram of Figure 1 illustrates the proposed measurement channel. The actual implemented blocks are: voltage controlled current source (VCCS), instrumentation amplifier (INA), demodulation and filtering, while the function generator and the data acquisition system are benchtop ones. The following sections will detail the design and implementation of each block.
2.1. Current source

The chosen current source was the Improved Howland, with a DC decoupling capacitor on the feedback network, as proposed by [8]. The implemented circuit can be seen in Figure 2. The input buffer is used to reduce the output impedance of the function generator, connected to $J2$. Capacitors $C8$ and $C10$ are gain compensation capacitors, used only with the AD8021 opamp, since the circuit tends to oscillate in higher frequencies. The ideal transfer function of the current source is $I_{LOAD} = V_{osc}/R1$.

2.2. Instrumentation amplifier

The instrumentation amplifier used is based on three discrete operational amplifiers, with FET inputs, like the AD8065/AD8066, from Analog Devices. This is due mainly to the fact that INAs with a higher bandwidth have digitally programmable gain, which would add complexity of hardware and software to the project. Besides, these amplifiers have a strong attenuation on their CMRR, reaching approximately 20 dB at 1 MHz for the AD8253, for example [1].

The topology is presented on figure 3, which also allows the implementation of a guardshield. According to [6], this technique allows a compensation of the degradation of the CMRR of the amplifier due to the different impedances of the source, and the different capacitances from the cable signals to the shielding. The signal transmission is balanced, since both cables are affected by the same noise sources, which shows up to the INA as a common mode voltage. The shielding is used to reduce differential noise pick up.

The ideal transfer function is unitary. Connectors $J2$ and $J3$ are the inputs for the sensing
electrodes, while connector J5 is the output for the demodulator. All capacitors shown are used for power supply decoupling.

2.3. Phase and quadrature demodulation
The phase and quadrature demodulation is done using the AD835, an analog multiplier from Analog Devices. It generates the linear product of the inputs X and Y, with a -3 dB bandwidth of 250 MHz. This kind of demodulation allows the use of low-cost data acquisition systems, since the sampled data will be a DC voltage. It can also be used for higher frequencies of operation, as long as the analog multiplier’s bandwidth is respected.

2.4. Low-pass filter
The choice of filter was a 4th-order Butterworth, for maximum bandwidth flatness, and of Sallen-Key topology, allowing gain adjustment independently of the filter’s frequency of operation. Two independent filters are needed, one for the phase demodulation, and one for the quadrature demodulation.

2.5. Printed circuit board
The matching of the resistances, both in the current source and in the instrumentation amplifier, demand careful design of the printed circuit boards to keep these traces as short as possible, and also symmetric. Special attention was given to the parasitic capacitances of the main high frequency nodes, the output of the current source and the input of the instrumentation amplifier, by keeping the power planes as far away as possible. Due to tight project schedule, the first prototypes were manually built, and are single sided.

3. Validation
The following figures present the waveforms on different points of the measurement channel. The amplitude of the function generator was 1 Vp, at 1 MHz, and the load resistance was 500 Ω.
The stable functioning of the Improved Howland circuit can be seen on Figure 4, showing its input and output waveforms. Next, figure 5 shows, on channel 1, the output of the current source, and on channel 2, the output of the instrumentation amplifier, with its unitary gain.

![Figure 4. Improved Howland waveforms. Channel 1: Function generator output; Channel 2: Improved Howland output.](image1)

![Figure 5. Improved Howland and INA waveforms. Channel 1: VCCS output; Channel 2: INA output.](image2)

On figure 6’s channel 1, the output of the instrumentation amplifier is shown against the output of the phase demodulation (channel 2). It is clear that the signal’s amplitude is halved, and a DC component of the same value shows up as the result of the demodulation procedure. This signal is then low-pass filtered and acquired digitally acquired as a DC voltage.

4. Characterization
The output of the phase demodulation was measured for 10 different frequencies, from 100 kHz to 1 MHz, for 10 purely resistive loads, from 100 Ω to 1 kΩ, totalling 100 acquisition procedures. For each procedure, 200 samples were averaged using a 10 Samples/s sampling rate, measured with an Agilent 34401A digital multimeter. The excitation signal was obtained from an Agilent 33210A function generator.

Characterizing the equipment for purely resistive loads only, any attenuation of the output

![Figure 6. Instrumentation amplifier and analog multiplier waveforms. Channel 1: INA output; Channel 2: Phase demodulation output.](image3)
voltage, in function of the frequency, will be due to static elements of the measurement channel, that are:

- parasitic capacitances of the printed circuit board;
- input parasitic capacitance of the instrumentation amplifier;
- degradation on the frequency response of the operational amplifiers;
- phase delay of the current source and INA circuits.

The injected sinusoidal waveform has an amplitude of 1 $V_p$, leading to a load current of 1 $mA_p$. We assumed that $R_1 = 1 \, k\Omega$, and that the amplitude of the function generator does not vary with frequency. Also, that the transfer function of the instrumentation amplifier, the analog multiplier and the low pass filter remains the same over the whole range of frequencies.

The block diagram of the experiment is shown in figure 7, followed by its benchtop implementation, on figure 8.

![Figure 7. Block diagram of the experiment.](image)

![Figure 8. Benchtop implementation.](image)

5. Results

The main reason for this characterization was to determine a minimum value for the output impedance of the current source, usually presented in literature as a means of comparison between different circuits and equipments. The first analysis made regarded linearity of the prototype, for all frequencies and load resistances. On figure 9 it can be seen that the equipment is linear over all its operating range. The fitting curve is only shown for the 100 kHz frequency to avoid crowding the graphic.

Load current can be seen on figure 10. Different colors represent different load resistances, presented with their ideal values, for clarity. Real values can be found on the tables at the appendix.

As expected, the load current shrinks with increasing frequency and load resistance, mainly due to parasitic capacitances that shunt it away from the load. Its value is always less than the ideal 1 $mA_p$, due to systematic errors of the measurement channel, like phase delays influencing the demodulation and the tolerance of the resistances. To clarify this errors, figure 11 shows the absolute error, as a function of frequency and load resistance. It is given by the difference between the ideal value and the experimental one, divided by the ideal value.

The absolute error is relatively high, varying from 4 % up to around 6 %. But, once this absolute error has been characterized, it can be software compensated, since it depends only on...
static elements of the measurement channel. Under this perspective, an analysis of the variation of the load current becomes more interesting, and is shown in figure 12.

The reference for calculating the variation is the load current value for a 100 Ω load, at 100 kHz, and it considers that the rest of the circuit is not affected by the operating frequency or by the load resistance. It is known that other factors will influence the degradation of the load current measured, such as phase delay of the current source and the instrumentation amplifier, for example. Anyway, a tendency of increasing variation, and consequently increasing error can be seen, as we increase load resistance and frequency. For the worst case, that in fact is for the highest frequency and load resistance, the maximum variation is inferior to -2.5 %.

This maximum variation could lead to the conclusion that the output impedance of the current source is greater than 40 kΩ, since the greatest load resistance is 1 kΩ. But, for that to be true, the current variation would have to be constant for all frequencies, resulting in a constant
inclination to the curve and an equal spacing between curves. But the output impedance varies with frequency, since it depends on factors such as the differential and common-mode open loop gain of the operation amplifier, as can be seen on figure 13.

In figure 13, it becomes clear that the output current shows different variations for the same load resistance variation, depending on the operating frequency. But, maybe not as explicit in the graphic is the fact that, for the same frequency, the circuit presents different values of output impedance, depending on the load resistance.

For example, between load resistances of 900 Ω and 1000 Ω, we have almost zero load current variation on the 200 kHz frequency. On the same frequency, with the load varying from 700 to 800 Ω, the load current variation is greater, around 0.25 %. The presence of this different derivatives on the curve could suggest a dependency of the output impedance of the current source with the load resistance, assuming that the other blocks of the circuit are not affected by
It is important to highlight that the output impedance being analysed is not only that of the current source, since the input capacitance $C_i$ of the instrumentation amplifier, typically 2 pF for the AD8065/AD8066 [2], is also present, besides the parasitic capacitances of the PCB. Since traditional methods of current measurement consist actually of measuring a voltage developed across a known resistance, any data acquisition system that is connected in parallel to the current source will inevitably alter its output impedance, shunting current away from the load. The effective characterization of the output impedance of the current source only, could be made measuring the current in an indirect form, with the use of magnetic field sensors, for example, disconnecting the instrumentation amplifier from the load. This approach presents its difficulties due to the few milliamp amplitude of the current used on bioimpedance systems.

5.1. Comparison
The graphics exposed first were obtained from Circuit 1. Characterization data was gathered on four different circuits, in an attempt to verify the influence of the following parameters on the overall performance of the measurement prototype:

- matching of resistances;
- open loop gain of the operational amplifiers;
- bandwidth of the operational amplifiers;
- printed circuit board.

The difference between the circuits can be seen on table 1.

Two prototypes of printed circuit boards were made, due to different component packages. Basically, prototype A was built for three AD8065, and individual 0805 packaged resistors, while prototype B was built for one AD8066 plus one AD8065, using matched resistors on a SO16 package [12]. The VCCS OpAmp mentioned is the one used on the current source.

6. Conclusion
This paper presented the design, implementation and characterization of a multi-frequency bioimpedance measurement prototype. It was the author’s undergraduate Electrical Engineering
Table 1. Four different characterized circuits.

| Printed Circuit Board | Circuit 1 | Circuit 2 | Circuit 3 | Circuit 4 |
|-----------------------|-----------|-----------|-----------|-----------|
| VCCS OpAmp            | AD8038    | AD8021    | AD8038    | AD8038    |
| Resistor Matching     | 1%        | 0.05%     | 0.05%     | 0.05%     |
| Min. Absolute Error   | 3.93%     | 4.05%     | 3.80%     | 3.68%     |
| Max. Absolute Error   | 6.20%     | 6.14%     | 6.15%     | 5.55%     |
| Max. Load Current Var.| -2.37%    | -2.04%    | -2.34%    | -1.93%    |

final project, and also the first step on the construction of an electrical impedance tomograph at the Biosignals Laboratory at UCS, where it can complement the works already being made on EEG.

During the implementation, we could prove the functioning of the measurement channel on the desired frequency and load ranges, demodulating the high frequency signals through analog multipliers. Besides that, the characterization procedure showed some interesting results that need further analysis, specially on the behavior of the current source. The best results were obtained on a single sided PCB, using the AD8038 op-amp, 0.05 % tolerance resistors, resulting in a maximum absolute error of 5.55 % and a maximum load current variation of -1.93 %. We believe that the main limitation for improving these results reside on the input parasitics of the instrumentation amplifier that will always shunt some current away from the load.

The degrading effect of higher frequencies on the measurement channel was clear, mainly due to the parasitic capacitances of the current source and the input of the instrumentation amplifier. Future works on this project may include the integration of a Direct Digital Synthesizer as function generator, and the construction of an acquisition system and a graphical user interface that allows the equipment to be operated by lay users. Since many biological tissues have known conductivity values, it could be used on those tissues as another way to validate the measurements.

Another interesting point to verify would be the sensibility of the output impedance of the current source against the open loop gain of the operational amplifier, and the variation of each resistance. Other analysis that could be done is the possible dependency of the current source and the load resistance. The characterization of each circuit block individually could contribute to answer these questions.

Appendix

Experimental data gathered on the four implemented circuits can be seen on Figures A1, A2, A3, A4. The first two lines are the ideal and real values of the resistances, in Ω. The following lines are all voltage measurements, in V. The last line represents the DC offset of the analog multipliers’ output, in V.

References

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Northwood, MA 02062-9106, U.S.A.
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[4] Boone K G and Holder D S 1996 Current approaches to analogue instrumentation design in electrical impedance tomography Physiological Measurement, v. 17, p. 229-247.
Figure A1. Data results from characterization 1.

![Figure A1](image1.png)

Figure A2. Data results from characterization 2.

![Figure A2](image2.png)

Figure A3. Data results from characterization 3.

![Figure A3](image3.png)

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| Ideal | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|       |     |     |     |     |     |     |     |     |     |      |
| Real  | 100.0661 | 200.537 | 300.0935 | 400.6675 | 501.01 | 600.317 | 700.084 | 800.355 | 900.085 | 1000.27 |
| 100kHz| 0.08620155 | 0.11019625 | 0.1787486 | 0.2476127 | 0.3275412 | 0.4229914 | 0.5270852 | 0.6386273 | 0.7622765 | 0.918484 |
| 200kHz| 0.08272835 | 0.10604265 | 0.1580615 | 0.2267506 | 0.3042955 | 0.3824211 | 0.4700717 | 0.5683834 | 0.665343 | 0.761374 |
| 300kHz| 0.08169925 | 0.10507885 | 0.1581494 | 0.2269340 | 0.304397 | 0.382544 | 0.4700775 | 0.5683834 | 0.665343 | 0.761374 |
| 400kHz| 0.08176279 | 0.10511375 | 0.1782389 | 0.2465098 | 0.3237568 | 0.4012496 | 0.489954 | 0.5882956 | 0.687644 | 0.787613 |
| 500kHz| 0.0828586 | 0.1062829 | 0.1781228 | 0.261263 | 0.340848 | 0.4378564 | 0.531233 | 0.6318457 | 0.732045 | 0.832937 |
| 600kHz| 0.0830656 | 0.1064175 | 0.1787655 | 0.261171 | 0.3573564 | 0.4510847 | 0.551912 | 0.6534045 | 0.756709 | 0.859913 |
| 700kHz| 0.0826648 | 0.1060225 | 0.1780523 | 0.260999 | 0.350861 | 0.4531635 | 0.551912 | 0.6534045 | 0.756709 | 0.859913 |
| 800kHz| 0.0820999 | 0.1061515 | 0.1781545 | 0.260003 | 0.3500803 | 0.4531635 | 0.551912 | 0.6534045 | 0.756709 | 0.859913 |
| 900kHz| 0.0826797 | 0.10601355 | 0.1797876 | 0.265536 | 0.3625422 | 0.4580579 | 0.567621 | 0.6745803 | 0.781512 | 0.882692 |
| 1000kHz| 0.0826523 | 0.10602665 | 0.17795345 | 0.258555 | 0.3273727 | 0.36307043 | 0.413957 | 0.5607065 | 0.699597 | 0.846699 |
| Offset| 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 | 0.03461495 |

Figure A4. Data results from characterization 4.

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