Minimal implementation of an AFE4300-based spectrometer for electrical impedance spectroscopy measurements

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Abstract. The AFE4300 is a new low-cost on-chip impedance spectrometer developed by Texas Instruments able to handle multiple four electrode interface measurements. In this work, we present a brief description and characterization of this device and, besides its interesting features as a body-composition impedance meter system, we evaluate its potential to develop minimal implementations for other biomedical applications. As the case study presented in this paper, its use to monitor ventilatory time-varying bioimpedance.

1. Introduction
Over the past several years, electrical bioimpedance has gained popularity for its potential use in a wide range of applications [1]. Impedance-based devices have been developed for many applications [2], e.g. body composition analysis [3], electrical impedance myography [4] or impedance cardiography [5] to name but a few. Although in practice most studies are conducted with high-performance devices, in some cases, minimum size instrumentation is required, as for example in wearable bioimpedance applications. For that, Texas Instruments has released the AFE4300, a new system on-chip fully integrated electrical impedance spectrometer initially designed for body composition determination in commercial weight scales.

The AFE4300 is a 4-electrode measurement device (see the principle of operation in figure 1) that enables multiple impedance measurement configurations through the internal multiplexers. To perform single or multi-frequency impedance spectroscopy measurements, the user can select either the full wave rectifier (FWR) or quadrature and phase (I/Q) demodulators. The peak-to-peak value of the injected sinusoidal current can be limited with an external resistor. The excitation signal is internally generated using an integrated Direct Digital Synthesizer (DDS) and the frequency can be modified by registers. The voltage drop is sensed through the high and low voltage channels. The clock for the device is generated from an external reference clock.
Figure 1. AFE4300 functional block diagram for tetrapolar single- or multi-frequency body impedance measurements.

Figure 2. Response of the FWR demodulator as a function of load resistance (measured at 8 kHz) and electrode impedances $Z_e = [0, 100, 200]$ (Ω).

2. Experimental results

2.1. Characterization

With the purpose of evaluating the performance of the AFE4300 to measure impedance, we proceed to perform a series of experimental measures using the evaluation board provided by the manufacturer. In order to determine the linearity range of the device, we measure using the FWR demodulator a set of pure resistors from 100 Ω to 1 kΩ (1%) without considering electrode impedance resistors ($Z_e = 0$Ω). This is done using a decade resistance box manufactured by Danbridge type CDR4/BCDE. We calibrate the FWR-voltage output with a two-point method performing a two-reference resistors measurements, 701.5 Ω and 196.8 Ω (1%), which takes into account the gain [Ω/V] and offset [V] factors. As shown in figure 2, the AFE4300 works in a linear region for the range of resistors measured. As regards the I/Q data, data are calibrated with the same two-reference resistors.

As for the robustness in front of electrode impedance, two electrode resistor values ($Z_e = 1000$Ω and $Z_e = 200$Ω) are also tested. The dummy electrode resistors are connected to the AFE4300 four-electrode impedance measurements terminals. The values of electrode impedance mismatch (50% mismatch of an electrode impedance) on the voltage sense channels are also tested (data not shown). As it may be observed in figure 2, the AFE4300 is able to handle with electrode impedances around hundreds of ohms behaving linear with the unknown impedance measured.

2.2. Impedance measurements in phantoms

Figure 3 (A) shows the ability of the AFE4300 to perform impedance spectroscopy measurements measuring a dummy circuit compared to a commercial HP4192 impedance analyzer. The
Figure 3. Accuracy in multi-frequency impedance measurements using the I/Q (A) and FWR demodulator in phantoms (B) and foot-to-foot body impedance measurements (C).

Table 1. Predicted Total Body Water (TBW), Fat-Free Mass (FFM) and Fat Mass (FM). Refer text for details.

| Subject | SFB7 | AFE4300 | SFB7 | AFE4300 |
|---------|------|---------|------|---------|
| TBW (L) | 45.48| 48.1    | 42.24| 43.0    |
| FFM (kg)| 62.13| 65.7    | 66.87| 58.7    |
| FM (kg) | 26.67| 23.1    | 28.59| 27.7    |

impedance measurement was based on a 4 electrode topology using I/Q demodulator and data were processed with MATLAB™ [6].

2.3. Body impedance measurements for body composition assessment

In table 1 are shown the reduced parameters for body composition assessment via the multifrequency Hanai-Cole approach for two male caucasian subjects, 29 and 50 years old, with body mass indices (BMI) of 23.84 kg/m² and 28.83 kg/m² respectively. As for the measurements performed with the SFB7 (Impedimed, San Diego, CA, USA), the measurement configuration were the standard distal body impedance analysis (BIA) configuration to foot-to-foot with the patient in supine decubitus position (3 kHz → 500 kHz). The four electrodes were placed on the right and left foot in the third metatarso-phalangeal and in the articulation, 6 cm apart. Disposable pregeled Ag/AgCl electrodes were used (3M Red Dot). As for the AFE4300 measurements, the device was connected to the electrodes of a Tanita TBF-611 commercial weight scale and the subjects were in upright position. The AFE4300 current level applied was
of 100 uA. The standard errors (SE) of the Cole model parameters were estimated from the fitting in figure 3 (B) – (C). The relative errors in the estimation of \( R_0 \) and \( R_{\infty} \) are 0.34% – 0.55% and 0.71% – 2.49% respectively. The frequency sweep electrical impedance spectroscopy measurement performed is measured at 18 frequencies within the range 2 kHz → 100 kHz (see an example in figure 3 (C)).

### 2.4. Respiratory activity monitoring

To monitor time-varying bioimpedance-based respiratory activity, we measure the hand-to-hand impedance using Shieldex P180 textile electrodes manufactured by Statex placed on a handlebar. A current injection (100 uA, 32 kHz) was applied through the high potential - current electrodes and the voltage was measured with the low potential - current electrodes. The textile electrodes are fabric made of 78% Nylon, 22% elastomer and plated with 99.9% conductive silver with an average surface resistivity 5 Ω per square with two directional stretchability (wrap-weft). The respiratory characteristics of the sampled \( (f_s=475 \text{ sps}) \) voltage signal is shown in figure 4.

The periodic reconstruction of the voltage signal measured shown in figure 4 (left, blue) is obtained estimating the mean periodicity of the signal in the frequency domain. The discrete Fourier transform (DFT) is calculated an plotted in figure 4 (right, blue). Further, only the harmonics corresponding to an integer number of the mean periodicity were retained, and the leftovers of the DFT spectrum were set to zero (right, red). The reconstructed periodic time varying (PTV) domain voltage signal was then obtained using the inverse of the reconstructed DFT (iDFT) spectrum (left, red).

### 3. Conclusions

Ultimately, the results show the ability of the AFE4300 to acquire the stationary and nonstationary behavior of bioimpedance. Unlike the AD5933 from Analog Devices, the AFE4300 does not need an external front-end to measure at 4-electrodes [7]. The reduced size and complexity of the electronics of the device widens the possibilities for the measurement of electrical impedance with minimal implementations.

### References

[1] Schwan H P 1999 *Ann. New York Acad. Sci.* **873** 1–12

[2] Martinsen O G and Grimnes S 2008 *Bioimpedance and Bioelectricity Basics, Second Edition* (Academic Press)

[3] Jaffrin M Y and Morel H 2008 *Med. Eng. & Phys.* **30** 1257–69

[4] Rutkove S B 2009 *Muscle nerve* **40** 936–46

[5] Kubicek W G, Karnegis J N, Patterson R P, Witsoe D A and Mattson R H 1966 *Aerospace medicine* **37** 1208–12

[6] MATLAB 2012 *version 8.0.0 (R2012b)* (Natick, Massachusetts: The MathWorks Inc.)

[7] Seoane F, Ferreira J, Sanchéz J J and Bragós R 2008 *Physiol. Meas.* **29** S267–78