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Adopting a Better Bioimpedance Analog Front End for Next-Generation Vital Signs Monitoring Devices

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Abstract

Vital signs monitoring (VSM) devices perform real-time measurement of the user's electrocardiogram (ECG), photoplethysmogram (PPG), bioimpedance, and other parameters. Among them, bioimpedance is an important electrical parameter that characterizes the user's physiological characteristics and vital signs, and is widely used in many detection fields. This article introduces the basic concepts, application scenarios, and current pain points of bioimpedance measurement. A new measurement solution is also introduced in this article, and the analog front end (AFE) used in the solution supports outputting sinusoidal sweep stimulus and quadrature demodulation, thereby improving the accuracy and convenience of bioimpedance measurement. At the same time, the AFE can also perform synchronous measurements with other biosensors, simplifying the design of next-generation VSM systems.

Introduction

Bioimpedance refers to the impedance change of organisms or their tissues, organs, and cells, when a stimulus below their safe threshold is applied. It is usually a complex impedance that changes with frequency. Bioimpedance measurement is noninvasive and low cost, simple to operate, and supports a wide range of functions. It is easy for doctors and patients to accept and has a high level of clinical applications.

At present, VSM has gradually extended from medical healthcare equipment to portable consumer products. People can now understand their own physiological conditions anytime and anywhere with VSM devices. VSM has been widely used in remote medical care, disease prevention, auxiliary diagnosis, and health fitness. It can measure various physiological signals such as ECG, PPG, bioimpedance, and skin temperature. These signals can be used to calculate and analyze heart rate, peripheral oxygen saturation, blood pressure trending, respiration, mental stress, and so on. Bioimpedance is usually combined with other physiological signals to evaluate the user's health status completely and comprehensively.

Human Body Bioimpedance and Its Physiological Significance

All substances have a certain opposition effect to the current passing through them. This effect is called the impedance of the substance. To achieve accurate calculation and measurement of human body bioimpedance, it is necessary to model the human body as a circuit composed of passive devices such as resistors and capacitors. That is the equivalent model of human body bioimpedance. So how can human body bioimpedance be translated into an equivalent circuit model?

First, we study the components of the equivalent model. Human tissue is composed of cells. Since the intracellular fluid (ICF) and extracellular fluid (ECF) have good electrical conductivity, they can be equivalent to two resistors as R_I and R_E. The cell membrane is mainly composed of lipids, and there is a transmembrane voltage difference between its inside and outside, so it can be equivalent to a capacitor as C_M. Therefore, the human body bioimpedance has both resistance and capacitance components, which give it a complex impedance. Then, we study the specific structure of the equivalent model. As shown in Figure 1, the cell membrane can be regarded as a capacitor. Low frequency current (purple dotted line) has difficulty passing through the capacitor, so it cannot pass through cells and can only flow in the ECF. At the same time, also due to the capacitor, high frequency current (green solid line) can flow in the ICF through cells directly. Therefore, we can express the bioimpedance equivalent model of the human body as the circuit shown in Figure 1. High frequency current can pass through C_M and R_I, while low frequency current can only pass through R_E.

R_E, R_I, and C_M are cell-level parameters that can reflect some health status. R_E is related to the volume of ECF, while R_I is related to the volume of ICF. For R_E, a smaller R_E represents a larger ECF volume, commonly in tissue edema, ascites, or organ failure. A larger R_E is usually found in dehydration. For R_I, a smaller R_I

represents a larger ICF volume. Since muscle cells have a higher water content than fat cells, a smaller R_I is commonly seen in people with developed muscles. On the contrary, people with high body fat usually have a larger R_I. C_M reflects the integrity of the cell membrane. A larger C_M often represents good cell function, while a smaller C_M indicates poor cell function.

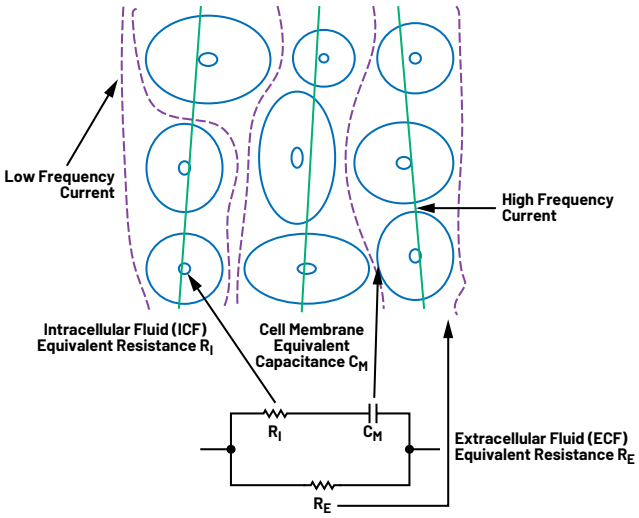

Figure 1. A human body bioimpedance equivalent circuit model.

In Figure 1, we can see that human body bioimpedance Z is a complex impedance, which can be expressed as

$$Z = R + jX \quad (1)$$

And its polar form is

$$Z = |Z| \angle \varphi \quad (2)$$

Here, the real part of Z is the resistance R, and the imaginary part is the reactance X. R mainly represents the overall water content of the human body, while the absolute value of X mainly represents the overall tissue density. The modulus of Z is |Z|, and the phase angle is φ. A smaller |Z| often indicates higher water content, tumors, or inflammation, while a larger |Z| indicates a dehydration state, tissue necrosis, or damage. The absolute value of φ can reflect the nutritional status of the human body, and a lower value usually indicates malnutrition.

According to the equivalent circuit model in Figure 1, R_I and C_M are connected in series and they are connected in parallel with R_E. So interested readers can get

$$Z = (R_I + C_M) || R_E \quad (3)$$

If we expand Equation 3 in the form of complex impedance, and combine it with equations 1 and 2, we can further express R, X, |Z|, and φ as functions of ω, namely

$$R = \frac{R_E + \omega^2 (R_E + R_I) R_E R_I C_M^2}{1 + \omega^2 (R_E + R_I)^2 C_M^2} \quad (4)$$

$$X = - \frac{\omega R_E^2 C_M}{1 + \omega^2 (R_E + R_I)^2 C_M^2} \quad (5)$$

$$|Z| = \sqrt{\frac{R_E^2 + \omega^2 R_E^2 R_I^2 C_M^2}{1 + \omega^2 (R_E + R_I)^2 C_M^2}} \quad (6)$$

$$\varphi = - arctan \frac{\omega R_E C_M}{1 + \omega^2 R_I (R_E + R_I) C_M^2} \quad (7)$$

Here ω is the angular frequency of the stimulus signal. The plot of the previous parameters changing with the angular frequency is shown in Figure 2.

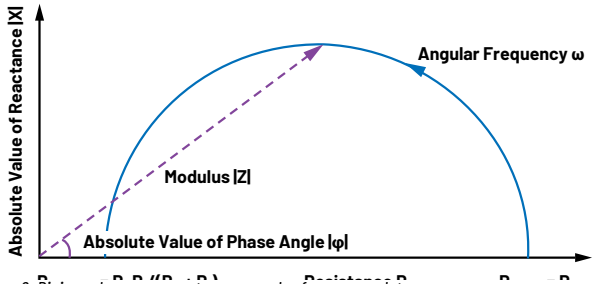

Figure 2. Bioimpedance parameter vs. angular frequency plot.

Since R_E, R_I, and C_M are microcosmic parameters in the cell level, they cannot be measured directly. However, R, X, |Z|, and φ can be measured by the methods introduced in the following sections. Therefore, these equations and Figure 2 can not only quantitatively determine the relation between parameters (namely R, X, |Z|, and φ) and the angular frequency, but also help us calculate R_E, R_I, and C_M indirectly. This associates the macrocosmic human body with the microcosmic cells. To conclude, these equations can facilitate the user in assessing their health status comprehensively and completely by bioimpedance measurements. The physiological significance of bioimpedance parameters is summarized in Table 1.

Table 1. Physiological Significance of Bioimpedance Parameters

Bioimpedance	Parameter	Physiological Significance
Microcosmic Parameters $Z = (R_I + C_M) \| R_E$	ECF equivalent resistance R_E	High: dehydration Low: edema/ascites/ organ failure
	ICF equivalent resistance R_I	High: high body fat Low: low body fat
	Cell membrane equivalent capacitance C_M	High: good cell function Low: poor cell function
Macrocosmic Parameters $Z = R + jX = \|Z\| \angle \varphi$	Resistor R	High: low overall water content Low: high overall water content
	Absolute value of reactance X	High: high overall tissue density Low: low overall tissue density
	Modulus |Z|	High: dehydration/tissue necrosis/tissue damage Low: high water content/ tumor/inflammation
	Absolute value of phase angle φ	High: good nutritional status Low: malnutrition

Current Bioimpedance Measurement Solution and Its Pain Points

In light of the importance of bioimpedance, it is necessary to measure all bioimpedance parameters accurately. According to Ohm's law, the measurement of an impedance usually uses voltammetry. Therefore, we can use a bioimpedance measurement integrated circuit (IC) to send a current signal to the human body as the stimulus and measure the response voltage at the same time, as shown in Figure 3.

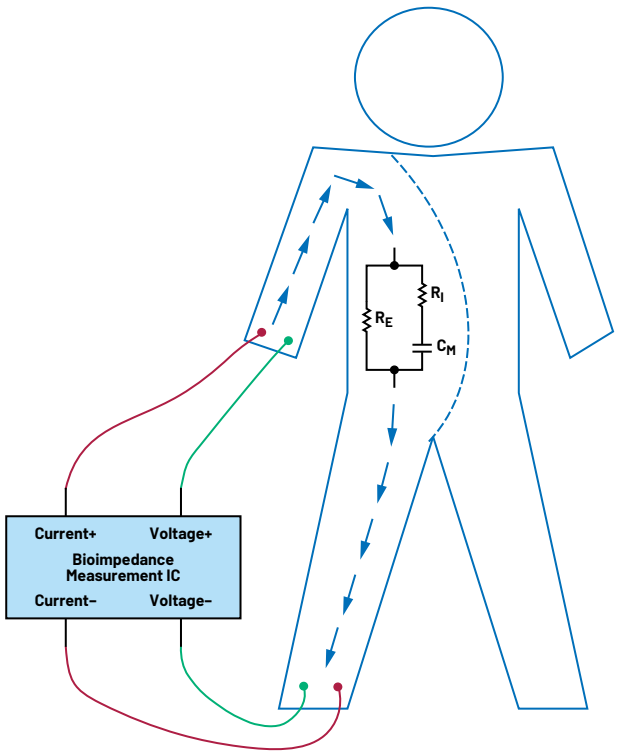

Figure 3. Voltammetry bioimpedance measurement.

Traditional bioimpedance measurement often uses the single-frequency measurement method. It only uses a sinusoidal signal of one fixed frequency as the stimulus. This method is simple to operate, but cannot obtain the details of bioimpedance that changes with frequency. As previously shown, bioimpedance involves a complex number that changes with frequency. Therefore, in order to accurately measure bioimpedance in the whole frequency domain, the frequency of the stimulus signal must cover the range from direct current (DC) to a relatively high frequency, rather than a fixed one.

In the face of this pain point, most current measurement solutions use a periodic square wave pulse with one fixed frequency as the stimulus. A typical solution is shown in Figure 4. The system power supply comes from the universal serial bus (USB) interface or battery, and outputs stable power by a low dropout (LDO) regulator. The microcontroller unit (MCU) sends square wave pulses to the body through skin electrodes and measures the response with a built-in analog-to-digital converter (ADC). The measurement results can be transmitted and displayed on mobile phones, computers, and other terminals by the Bluetooth® module. The first advantage of this solution is that the stimulus signal is easy to generate in a simple system configuration. It can be easily done based on the MCU. The second advantage is that, in the frequency domain, the square wave signal is actually a superposition of sinusoidal signals of many frequencies. Therefore, only using a square wave stimulus of one frequency can achieve the effect of multifrequency sinusoidal wave measurement, as shown in Figure 5.

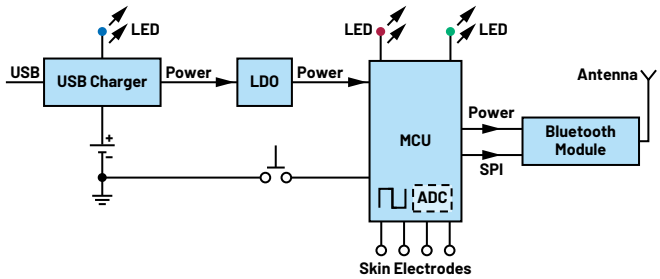

Figure 4. Current bioimpedance measurement system.

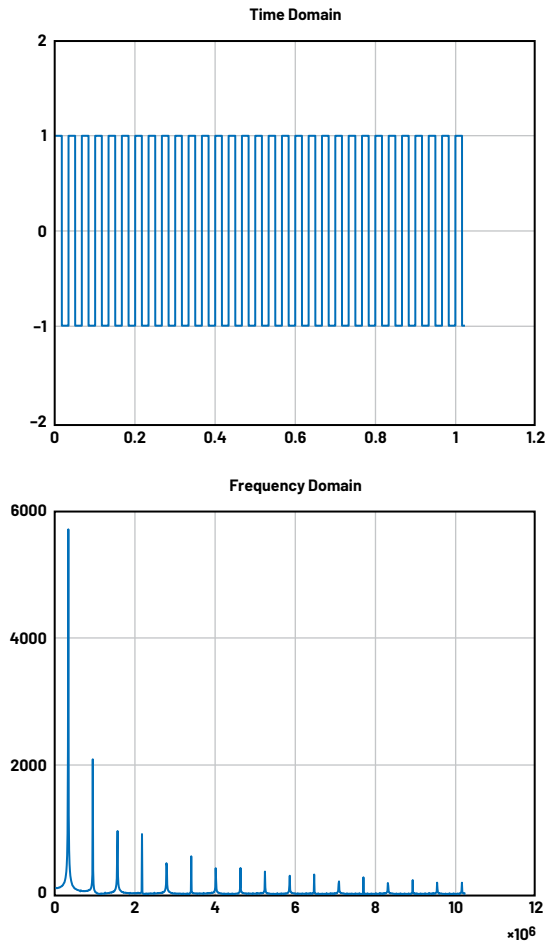

Figure 5. The time/frequency-domain waveform of a periodic square wave.

Despite many advantages, this solution still has many disadvantages. First, according to Figure 5, compared with the amplitude of the fundamental wave and the second harmonic wave, the higher harmonics of the square wave decreases very quickly. This means that high frequency signals will be interfered with by more noise, making it difficult for the ADC to extract effective response signals. Second, the actual stimulus frequencies of the square wave

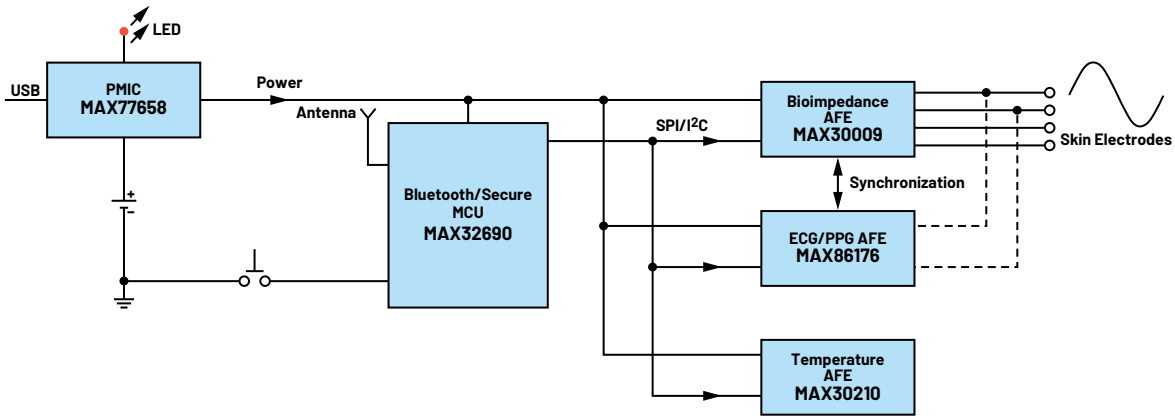

Figure 6. Sinusoidal sweep bioimpedance measurement system.

measurement are only the integer multiples of its fundamental frequency. If it is required to study a more universal case where the stimulus frequency is not the integer multiple, it may be necessary to adjust the stimulus frequency, which may result in re-development of the firmware. Third, limited to the clock frequency, the output frequency and sampling frequency of the MCU are not high enough, which may not be suitable for some application scenarios that require high stimulus frequencies. Fourth, the main function of the MCU is control or calculation. Compared with application-specific ICs, the accuracy of its internal ADC is very limited. These shortcomings make the current measurement solution impossible to accurately, conveniently, and completely measure R, X, |Z|, φ, and their relations to the stimulus frequency. It brings inconvenience to in-depth assessment of human health status. Last but not least, VSM devices are becoming more and more integrated, and the current solution can only measure bioimpedance but cannot measure other physiological signals simultaneously.

Highlighted IC and Its Benefits

However, the solution using a sinusoidal sweep stimulus can avoid the previous four inferiorities well, such as poor high frequency characteristics, inability to coordinate measurements with other sensors, and so on. This solution uses a specific purpose AFE to output sinusoidal stimulus currents whose frequencies cover the range from DC to a high frequency. It has many benefits. First, the stimulus frequency can be flexibly configured and is no longer limited to a specific fundamental frequency or its multiples. Second, the solution using square wave has the shortcoming of reduced stimulus amplitude in the high frequency band. In view of this, the stimulus amplitude in this solution can be flexibly adjusted to improve the measurement accuracy in the high frequency band. In addition, considering that the human body can be seen as a complex impedance, the resistance and reactance are orthogonal on the complex plane. This solution can also conveniently demodulate the response signal into two channels with a phase difference of 90° by quadrature demodulation, to calculate bioimpedance parameters conveniently.

A typical improved solution is shown in Figure 6. The system uses a power management integrated circuit (PMIC) to manage the power rails and MCU with Bluetooth and data security to control the bioimpedance AFE MAX30009 and other biosensors. In addition to the advantages mentioned before, this system has many other benefits. First, the AFE can work with ECG or PPG biosensors to achieve synchronous measurements, thereby realizing the function of measuring multiple vital signs in one system. Second, the MCU integrates Bluetooth and security functions,

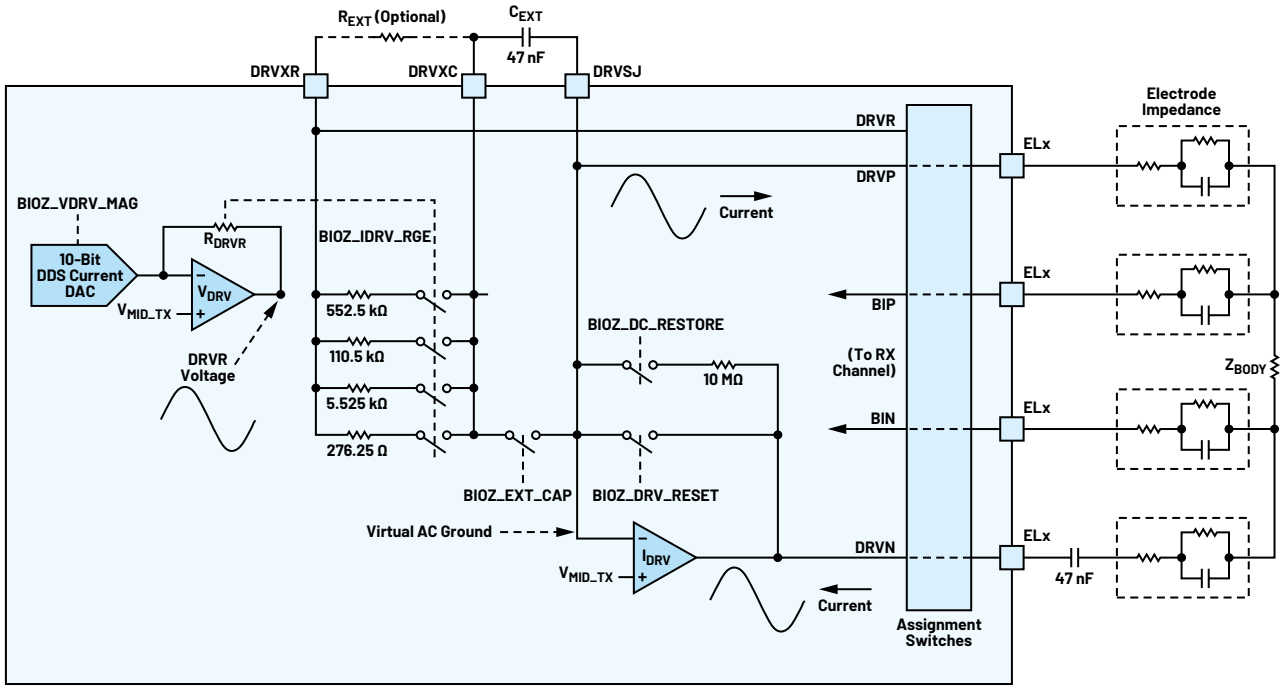

Figure 7. Bioimpedance transmit channel.

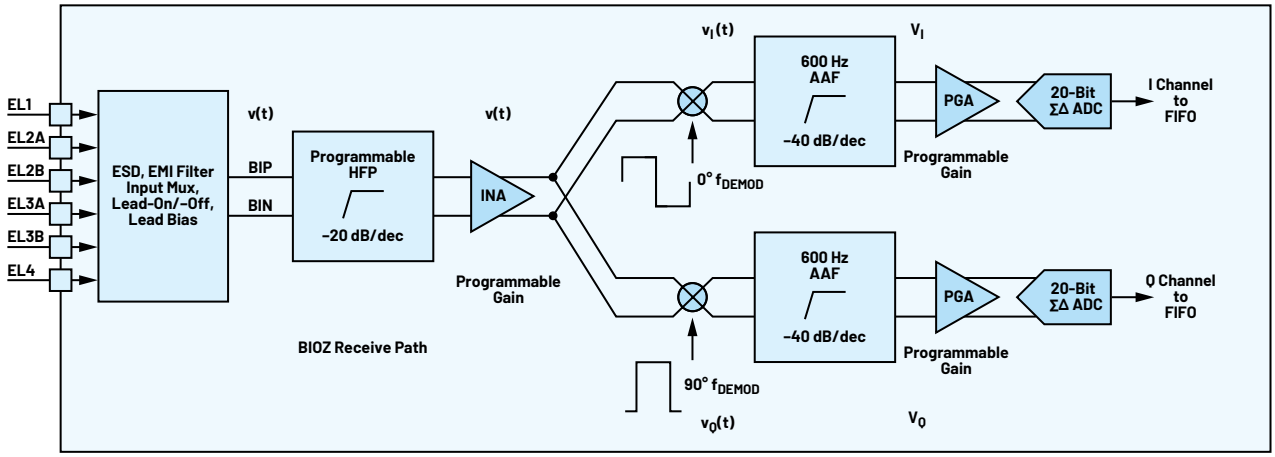

Figure 8. Bioimpedance receiving channel.

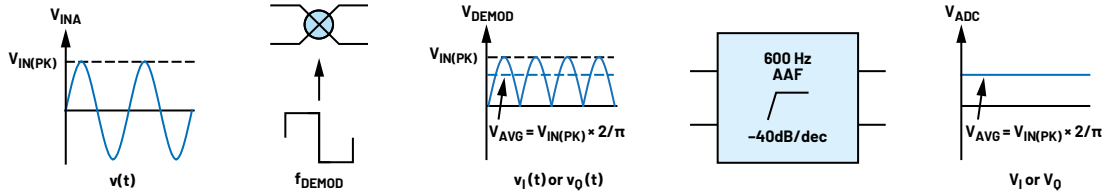

Figure 9. Quadrature demodulation.

so there is no need to use additional Bluetooth or secure authentication modules. It can ensure the secure transmission of private health information. Third, the PMIC integrates a charger, a fuel gauge, LDO regulators, and DC-to-DC converters, which can integrate the functions of many different kinds of power ICs into one single IC to save the system size.

Here, we use the internal block diagram of the bioimpedance AFE to illustrate the basic steps and principles of sinusoidal sweep bioimpedance measurement. Figure 7 shows the AFE transmit channel that outputs the stimulus current. The AFE uses an internal direct digital synthesizer (DDS) and digital-to-analog converter (DAC) to generate a sinusoidal sweep voltage with an adjustable frequency, which is converted into a current stimulus by a bias resistor and then applied to the human body. The response signal is measured by the AFE receiving channel through the receiving pins. The amplitude of the stimulus current can be controlled by four internal bias resistors or one external bias resistor. Internal bias resistors are 552.5 kΩ, 110.5 kΩ, 5.525 kΩ, and 276.25 kΩ, respectively. These four internal bias resistors correspond to four stimulus current amplitudes. The smaller the resistance, the larger the amplitude. In addition to the internal bias resistor, the user can also adopt an external bias resistor to determine the stimulus current amplitude freely.

The AFE also supports quadrature demodulation of the response signal. Quadrature demodulation divides the response voltage v(t) into two channels with a phase difference of 90°, thereby obtaining |Z| and φ. Figure 8 shows the demodulation process. The receiving channel mainly consists of a bypassable and programmable analog high-pass filter (HPF), an instrumentation amplifier (INA) with programmable gain, two quadrature demodulators, two antialiasing filters (AAF), two programmable gain amplifiers (PGA) and two ADCs. HPF and INA are used to reduce the noise and improve common-mode rejection ratio (CMRR). Two quadrature demodulators respectively multiply the received response voltage v(t) with two square waves, which have the same frequency as v(t) but a phase difference of 90°, to generate voltages of two channels. They are $v_I(t)$ of in-phase channel (I-channel) and $v_Q(t)$ of quadrature channel (Q-channel), respectively. Since the AAF is a two-pole, low-pass filter with a corner frequency that is much smaller than the signal frequency, it can extract the average value of $v_I(t)$ or $v_Q(t)$ to the next-stage ADC for sampling, as shown in Figure 9. For convenience, we can ignore the gain of filters and amplifiers in the signal chain here, so the output signal of the INA is still v(t). We use V_I and V_Q to represent the output voltages of the AAF, respectively, and can derive that |Z| and φ are

$$|Z| = \frac{\pi}{2I} \times \sqrt{V_I^2 + V_Q^2} \quad (8)$$

$$\varphi = arctan \frac{V_Q}{V_I} \quad (9)$$

Therefore, we can calculate |Z| and φ at different frequencies according to equations 8 and 9 by sending sinusoidal sweep stimulus currents to the bioimpedance and then quadrature demodulation. Then we can calculate other parameters of bioimpedance, namely R_E, R_I, C_M, R, and X, as well as their relations to the angular frequency like the one shown in Figure 2, according to equations 1 to 7. The most significant advantage of this solution is that all parameters can be measured or calculated accurately and completely, and the stimulus frequency and amplitude can be freely determined, compared with traditional solutions having low signal-to-noise ratio (SNR) in the high frequency band.

In addition, the AFE has many other advantages. First, the AFE still retains the function of outputting a square wave stimulus, which helps with easy upgrading and replacement. Second, as shown in Figure 6, compared with traditional solutions, the AFE's dedicated synchronization pins can share clock signals with other ECG or PPG biosensors to achieve synchronous measurement of multiple vital signs. This advantage can improve the integration and scalability of VSM devices. Third, the AFE can reuse the electrodes of the ECG biosensor to reduce the size of the system and improves portability.

Bioimpedance Measurement Applications

The bioimpedance measurement solution built by the MAX30009 has a wide range of application scenarios. They can be mainly divided into four categories: bioimpedance spectroscopy (BIS) or bioimpedance analysis (BIA), respiration,

Table 2. Bioimpedance Measurement Applications

Parameter	BIS/BIA	Respiration	GSR/EDA	ICG
Bioimpedance Range	10 Ω to 5 kΩ	10 Ω to 5 kΩ	50 kΩ to 10 MΩ	5 Ω to 50 Ω
Stimulus Frequency Range	1 kHz to 1 MHz (5 to 15 frequencies, typ)	50 kHz to 500 kHz (75 kHz, typ)	DC to 400 Hz (Single frequency)	20 kHz to 200 kHz (75 kHz, typ)
Stimulus Type	Sinusoidal wave	Sinusoidal wave Square wave	Sinusoidal wave	Sinusoidal wave
Bioimpedance Signal Band	DC	0.05 Hz to 4 Hz	DC to 1 Hz	DC to 20 Hz
Electrode	4 dry 4 wet	2 wet 4 dry 4 wet	2 dry	4 wet
Placement	Arm to arm Leg to leg Arm to leg Wrist to wrist	Either side of chest	Across palm Across finger Across wrist	Neck to abdomen

galvanic skin response (GSR) or electrodermal analysis (EDA), and impedance cardiogram (ICG). Each of these categories require a different impedance range, stimulus frequency range, stimulus type, impedance signal band, electrode type, and placement, as shown in Table 2.

Among them, BIS or BIA should reflect the details of all bioimpedance parameters in a wide frequency range accurately, and generate their plot looks like the one in Figure 2. Therefore, we usually select a dozen frequencies to perform sinusoidal sweep bioimpedance measurement in the frequency range from 1 kHz to 1 MHz. BIS or BIA is commonly used in body fat analysis, body moisture analysis, and so on.

The principle of respiration measurement is that the chest impedance changes periodically during breath. Since people usually breathe between 10 to 60 times per minute, the respiration bioimpedance is a slow changing signal in a low frequency band between 0.05 Hz and 4 Hz. Either a square or sinusoidal signal can be selected as the stimulus, at a typical frequency of 75 kHz.

GSR or EDA are commonly used in mental stress monitoring devices like lie detectors that measure changing impedance caused by hand sweat when a person is tense. The devices usually requires dry electrodes, and a single frequency stimulus between DC and 400 Hz.

ICG is a noninvasive method that can indirectly calculate stroke volume and cardiac output based on the thoracic cavity impedance change during a cardiac cycle. It can be used together with ECG to evaluate cardiac function. Usually, four wet electrodes are placed on the neck and abdomen of the patient. A sinusoidal signal between 20 kHz and 200 kHz (typically 75 kHz) is used as the stimulus. With synchronization pins, the MAX30009 can work with other ECG biosensors to achieve a comprehensive assessment of heart health. It can also reuse the skin electrodes of ECG biosensors.

Conclusion

Bioimpedance is one of the most important parameters for VSM. It is closely related to people's health status. Therefore, accurate bioimpedance measurement is of great benefit to maintaining health. The MAX30009 is a specific purpose device that can output many stimulus signals such as sinusoidal sweep. It supports the detailed measurement of bioimpedance parameters by quadrature demodulation, so has wide application scenarios. It can also achieve synchronous measurement with other biosensors and therefore has many advantages that traditional solutions do not have. It is an ideal product for constructing VSM applications. For further bioimpedance measurement products and information, please refer to the Bioimpedance Sensors Parametric Search and Body Composition, Hydration, Bioimpedance Analysis.

About the Author

Yi Xin is a senior central application engineer of China Central Application Center at Analog Devices and is responsible for support and application of healthcare biosensors, edge AI, and 1-Wire products. He graduated from Fudan University and the Chinese University of Hong Kong, with a Bachelor of Science in electronic information science and technology and a Master of Science in electronic engineering, respectively. Yi joined Maxim Integrated (now part of ADI) in 2018.