Weight-Scale and Body Composition Measurement Reference Design

TI Reference Designs

TI Reference Designs are mixed-signal solutions created by TI's experts. Verified Designs offer the theory, complete PCB schematic & layout, bill of materials and measured performance of the overall system.

Circuit Description

This document discusses the analog circuit design of weight-scale and body composition measurement applications. Two separate signal chains are discussed in this document: one for weight-scale (WS) measurements and the other for body composition measurement (BCM) analysis.

Design Resources

Design Archive (ZIP File)  All design files
AFE4300  Product Folder

1. Design Summary

This design takes a block level approach for designing a Weight Scale and Body Composition system.

1.1 Design Goal

Provide a Weight Scale and Body Composition system reference example.
2. Theory of Operation

2.1 Background on weight measurements

Weight-scale and body composition measurements are two separate signal chains, so weight-scale application will be discussed first. While there are multiple techniques for converting weight into an electrical signal, perhaps the most common is to use a resistive load cell configured as a Wheatstone bridge.

![Load Cell Bridge Sensor](image1)

Figure 1 Load Cell Bridge Sensor

Figure 1 shows a bridge configuration where one of the resistors in the bridge changes value as weight is applied. Depending on the construction of the bridge, more resistors may change value as weight is applied (four resistors at most for a Wheatstone bridge). Either way, an excitation voltage is applied across the top and bottom of the bridge. The output signal is measured as the differential voltage across the middle nodes. The challenge in designing a weigh-scale is how to make accurate measurements of the signal produced by the resistor bridge, because this signal is usually very small (mV magnitude).

Body composition is traditionally obtained by measuring the impedance across several points on the body and matching the result in a table linking both the impedance measured and the body composition. Bio-impedance is the response of a living organism to externally applied electric current. It is a measure of the opposition to the flow of that electric current through the tissues, the opposite of the electrical conductivity.

![Cell Bio-impedance model](image2)

Figure 2 Cell Bio-impedance model

The bio-impedance model of a cell is described in Figure 2, where Re is the extracellular resistance, Cm is the cell membrane capacitor, Rm is the cell membrane resistor, Ri is the intracellular resistance. The bio-impedance of cell is decided by various factors like cell size, shape, density, homogeneity etc.
To measure the bio-impedance, a high-frequency AC current is injected into the tissue through the drive electrodes (refer Figure 3). The AC current causes a potential voltage difference of the two receive electrodes [refer Figure 3]. This potential voltage difference is related to the resistivity of the tissue between the voltage-sensing or receive electrodes. The equivalent resistance is defined as the ratio of the voltage difference between the two receiver electrodes and the current that flows through the tissue.

2.2 Hardware overview and circuit description

2.2.1 Weight-Scale Analog Front-End

2.2.1.1 Overview and Gain Calculation

The weight-scale front-end has two stages of gain, with an offset correction DAC in the second gain stage. The reason for using INA and PGA is to fit different input voltage from the sensor bridge. Though not shown in the diagram, an anti-aliasing network is required in front of the INA to filter out electromagnetic interference (EMI) signals or any other anticipated interference signals. A simple RC network should be sufficient, combined with the attenuation provided by the on-chip decimation filter.
An internal reference source provides a constant voltage of 1.7V at the VLDO output to drive the external bridge. As the Wheatstone bridge has high source impedance and the output common-mode voltage is relative high, so the output of the bridge is connected to an INA (first stage). The good CMRR specification of the INA will reject the common-mode DC voltage at the bridge output and amplifying the differential signal voltage, the difference in voltage between the two lines only. The high input impedance and low bias current of the INA will reduce the error caused by measurement circuit to minimum.

The first-stage gain \( A1 \) is set by the external resistor \( R_g \) and the 100-kΩ \( \pm 15\% \) internal feedback resistors \( RFB1 \):

\[
A1 = (1 + 2 \cdot \frac{100k}{R_g})
\]

The second-stage gain \( A2 \) is controlled by feedback resistors \( RFB2 \), which have four possible values: 80kΩ, 160kΩ, 240kΩ, and 320kΩ. Because the gain is \( RF / 80kΩ \), the gain setting can be 1, 2, 3, or 4.

### 2.2.1.2 Input Common Mode Range

The usable input common mode range of the weight-scale front-end depends on various parameters, including the maximum differential input signal, supply voltage, and gain. The output of the first-stage amplifier must be within 250mV of the power supply rails for linear operation. The allowed common-mode range is determined by the equation:

\[
AVDD - 0.25 - \frac{GAIN \cdot V_{MAX,DIFF}}{2} > CM > AVSS + 0.25 + \frac{GAIN \cdot V_{MAX,DIFF}}{2}
\]

Where: \( V_{MAX,DIFF} \) = maximum differential input signal at the input of the first gain stage;

\( CM = \) Common-mode Range.

### 2.2.1.3 Input Differential Dynamic Range

The max differential \( (INP–INN) \) signal depends on the analog supply, reference used in the system. This range is shown in the equation below:

\[
MAX(INP−INN) < \frac{VREF}{GAIN}; \text{ Full − Scale Range} = 2 \cdot \frac{VREF}{GAIN}
\]

The gain in equation above is the product of the gains of the INA and the second-stage gain. The full-scale input from the bridge signal typically consists of a differential dc offset from the load cell plus the actual weight signal.

Having a high gain in the first stage helps minimize the effect of the noise addition from the subsequent stages. However, make sure to choose a gain that does not saturate the first stage with the full-scale signal. Also, the common-mode of the signal must fall within the range.

### 2.2.1.4 Offset Correction DAC

One way to increase the dynamic range of the signal chain is by calibrating the inherent offset of the load cell during the initial calibration cycle. The offset correction is implemented in the second stage with a 6-bit differential DAC, where each output is a mirror of the other and can source or sink up to 6.5µA. The effect at the output of the second stage is an addition of up to \( \pm 6.5\mu A \times 2 \times RFB2 \). This is equivalent to a voltage at the input of the second stage \( (A+ / A−) \) of up to \( \pm 6.5\mu A \times 2 \times 80kΩ = \pm 1V \), when \( RFB2 = 80kΩ \). Notice that this has no effect in avoiding the first-stage saturation. Because the offset correction DAC is a 6-bit DAC, the offset compensation step is \( 2V/2^6 = 31.2mV \) when referred to the input of the second stage.
Typically, a high-resolution analog-to-digital converter (ADC) then follows the PGA to digitize the amplified voltage. Given that the signals being measured usually are changing slowly, and that very high resolution is required, delta-sigma topologies are often used to implement the ADC. As with the gain stage, the stability of the ADC over time and temperature is very important so as not to limit overall performance.

2.2.2 Body Composition Measurement Analog Front-End

The AFE4300 provides two options for body impedance measurement: ac rectification and I/Q demodulation. Both options work by injecting a sinusoidal current into the body and measuring the voltage across the body. The portion of the circuit injecting the current into the body is the same for each of those options. The difference, however, lies in how the measured voltage across the impedance is processed to obtain the final result.

2.2.2.1 AC rectification

The top portion of Figure 5 represents the current-injection circuit. A direct digital synthesizer (DDS) generates a sinusoidal digital pattern with a frequency obtained by dividing a 1-MHz clock with a 10-bit counter. The digital pattern drives a 6-bit, 1-MSPS DAC. The output of the DAC is filtered by a 150-kHz, second-order filter to remove the images, followed by a series external capacitor to block the dc current and avoid any dc current injection into the body. The output of the filter (after the dc blocking capacitor) drives a resistor setting the amplitude of the current to be injected in the body:

\[ I(t) = \frac{V_{DAC}}{R_1} = A \sin(\omega_0 t) \]

Current flows into the body through an output analog multiplexer (MUX) that allows the selection of up to six different contact points on the body. The same MUX allows the connection of four external impedances for calibration. The current crosses the body impedance and a second MUX selects the return path (contact) on the body, closing the loop to the output of the amplifier.
At the same time that the current is injected, a second set of multiplexers connects a differential amplifier across the same body impedance in order to measure the voltage drop created by the injected current:

\[ V(t) = A|Z| \sin(\omega_0 t + \theta) \]

Where \( Z \) and \( \theta \) are the module and phase of the impedance at \( \omega_0 \), respectively.

The output of the amplifier is routed to a pair of switches that implement the demodulation at the same frequency as the excitation current source in order to drive the control of those switches. This circuit performs a full-wave rectification of the differential amplifier output and a low-pass filter at its output, recovers the dc level, and finally routes it to the same 16-bit digitizer used in the weight-scale chain.

\[ DC = \frac{2}{T} \int_{T/2}^{T} A|Z| \sin(\omega_0 t + \theta) \, dt = \frac{2A|Z|}{\pi} \]

Ultimately, the dc output is proportional to the module of the impedance. The proportionality factor can be obtained through calibration with the four external impedances. Although, with one single frequency or measurement, only the module of the impedance can be obtained; two different frequencies could be used to obtain both the real and the imaginary parts.

2.2.2.2 I/Q Demodulation

As explained previously, the portion of the circuit injecting the current into the body is the same for both configurations. Therefore, the circuit is the same in Figure 5 and Figure 6. The difference between them is that an I/Q demodulator is used in this second approach, as shown in Figure 6.

As with the case of the RMS detector, a differential amplifier measures the voltage drop across the impedance:

\[ V(t) = A|Z| \sin(\omega_0 t + \theta) \]
Where: $Z$ = the module of the impedance at $\omega_0$

$\theta$ = phase of the impedance at $\omega_0$

The I/Q demodulator takes the v(t) signal and outputs two dc values. These two values are used to extract the impedance module and phase with a single frequency measurement. Figure 6 shows the block diagram of the implementation. Using the I/Q demodulator helps reduce power consumption while yielding excellent performance.

3. Verification and measured performance

3.1 Health Hub Demonstration Suite

The figure below shows the Health Hub measurement setup hardware description. The app requires a PC, a BlueRadios USB Serial Dongle along with the Foot BCM data acquisition system. The pictured device connects to the app via Bluetooth low energy.

3.2 Health Hub App

3.2.1 Interface Overview

Health Hub is designed to allow the control and display of many BLE enabled health monitoring devices on a single screen. The screen is divided into multiple discrete areas, Figure 8, called Device Controls and each area allows a specific BLE enabled health monitoring device control.

3.3 Demonstration usage

Terminology:

*Advertising mode:* the Bluetooth radio is broadcasting advertising data; this allows another device to initiate a connection to the advertising device.

*Device:* a piece of hardware required for a demo.
Device control: The area on the screen of the app that controls a device.

3.3.1 Common Operations

Common operations apply to all of the demos with the Health Hub app.

3.3.1.1 Find Devices

The first step in initiating a connection to a Health Hub demonstration device is to have the PC finding the device. To this end, the desired device must be in advertising mode. Generally the devices will advertise any time they are turned on and not connected. When the Foot BCM is in advertising mode the display will be flashing. To find a device press the Discover Devices button as shown in the figure below. The icon will change to discovering and will find devices for about ten seconds.
3.3.1.2 Connection

The second step is to form a connection. Before finding a device by using Discover Devices the device controls appear as in the figure below.

![Figure 10 BLE enabled device not found](image)

Figure 10 BLE enabled device not found

After a device has been found the device control will appear as in the figure below.

![Figure 11 Device found – connection can be established](image)

Figure 11 Device found – connection can be established

When the Connect button is pressed a selector will be shown as below
When the desired device is selected from the list, the app will form a connection to the device over Bluetooth low energy. After connection the device control will open fully and control over the device can begin.

3.4 Measured Results

The device pictured below is the foot BCM device. The On/Off button is on the underside of the device covered by the device serial number. A short press of the On/Off button will turn the device on. A longer press of about a second is required to turn the device off. The On/Off status of the device can be verified by looking at the top of the device in the LCD window. The backlight will flash periodically while the device is powered ON.

The first step is the Calibration - press the “Calibrate” button. As in the figure below the button will change to “Scale Ready” when the calibration is complete. Even though the front panel of the GUI shows up the weight, height and age options it’s not necessary entering those values as the device is able to measure the weight.
The “Scale Ready” button indicates that the foot BCM device is ready to measure the user’s weight. Ask the subject to step on the scale and remain still. Press the measure button.

The following figure shows up some measurement results:
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949. ADDITIONAL TERMS AND CONDITIONS

Products

<table>
<thead>
<tr>
<th>Audio</th>
<th><a href="http://www.ti.com/audio">www.ti.com/audio</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
</tr>
<tr>
<td>Data Converters</td>
<td>dataconverter.ti.com</td>
</tr>
<tr>
<td>DLP® Products</td>
<td><a href="http://www.dlp.com">www.dlp.com</a></td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td><a href="http://www.ti.com/clocks">www.ti.com/clocks</a></td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
</tr>
</tbody>
</table>

Applications

| Automotive and Transportation | www.ti.com/automotive |
| Communications and Telecom | www.ti.com/communications |
| Computers and Peripherals | www.ti.com/computers |
| Consumer Electronics | www.ti.com/consumer-apps |
| Energy and Lighting | www.ti.com/energy |
| Industrial | www.ti.com/industrial |
| Medical | www.ti.com/medical |
| Security | www.ti.com/security |
| Space, Avionics and Defense | www.ti.com/space-avionics-defense |
| Video and Imaging | www.ti.com/video |
| TI E2E Community | e2e.ti.com |

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2013, Texas Instruments Incorporated