Signal Acquisition system using TI’s High Resolution SAR Converters

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SEM – Industrial Systems, Medical Sector
Leni Skariah
System Engineer in Industrial System / Medical

• Career
  – Master of Technology in Digital Electronics & Communication
  – At TI since 2015
  – Total 10+ years industrial experience in Sensing and Control & X-Ray Medical

• Expertise
  – Developing TI Design and other collaterals for Medical Application
  – Mixed signal board design and development
  – Precision Analog Design
  – Hardware/Software integration, system testing
Sanjay Pithadia
System Designer in Medical, Healthcare and Fitness Sector

• Career
  – Bachelor of Technology in Electronics engineering at VJTI, Mumbai, India
  – Joined TI’s Analog Applications Rotation Program in July 2008
  – Joined TI-India Sales/Apps team in Sept 2009
  – Joined Industrial Systems (Motor Drives) in April 2014
  – Joined Industrial Systems (Medical Sector) in August 2016
  – TI Designs: 19 Designs covering HV, LV Power, Signal Chain, Compliance based designs
  – Collaterals: 30+ App notes/Blogs/Articles

• Expertise
  – Responsible for developing subsystem design solutions for the Medical Healthcare and Fitness sector.
  – Involved in designing products related to energy, smart grid, industrial motor drives, and medical imaging.
  – Experience in analog design, mixed signal design, industrial interfaces, and power supplies..
Signal Acquisition system using TI’s High Resolution SAR Converters:
The report illustrates a differentially driven signal fed into TI’s 20 bit SAR ADC. This results in raw data available for data processing. This has zero latency and high linearity.

This TI design illustrate the CW Doppler signal conditioning for an ultrasound machine. The input signal bandwidth up to 100KHz and 128 differential signals from AFEs are summed together in a differential high speed amplifier and digitized with TI SAR ADC.

This presentation also addresses:
An adaptive circuit for adjusting the cut off frequency of anti-aliasing circuit in our explanations.
We also describe the SNR and ENOB of SAR ADC with oversampling and decimation.
We also include the schemes to sum the current outputs of the AFEs into differential amplifiers to include 128 channels.

What you’ll learn:
• Usage of high speed amplifiers interfacing to SAR ADC
• A relationship between ENOB, BW and SNR and details of post filtering
• Adaptive low pass filtering

Training level: Fundamental
Language: English
Audience: Application Engineers, Systems & design engineers
TI Designs, App notes & Parts Discussed:
• TID #’s: TIDA-01351, TIDA-01035, TIDA-01037
• Part #’s: ADS8900B, THS4551, REF5050, TPS709, TPS7A88
Detailed Agenda

• Introduction & Problem Statement
  – Overview of Ultrasound
  – Ultrasound Scanner
  – Ultrasound Modes of Operation
  – This TI Design describes data acquisition system which sums all the outputs of the AFEs and digitizes it with high SNR

• System solutions and design examples giving competitive advantage
  – Signal Acquisition System using TI’s high Resolution SAR ADC
  – A 20-bit Isolated Data Acquisition Reference Design Optimizing Jitter for Max SNR and Sample Rate
  – How to improve the SNR and ENOB of SAR ADC with oversampling

• TI Reference Designs and Collaterals to support the solutions
• Conclusion
Advantages
• Real-time & Non-invasive
• Non-Ionization Radiation
• Inexpensive
• Multi-channel in a single system
• Growing market of >4 billion worldwide

Operation Principles
• Ultrasound ~ 2-20MHz
• Transducer ~ Piezo Electric Transducer
Ultrasound Modes of Operation

There are four main modes of operation for ultrasound

- **A - Mode (Amplitude Mode)**
- **B - Mode (Brightness Mode)**
- **M - Mode (Motion Mode)**
- **D - Mode (Doppler Mode)**

- D mode is based on the Doppler effect, i.e., change in frequency (Doppler shift) caused by the reciprocal movement of the sound generator and the observer.

- Diagnostic ultrasound uses the change in frequency of ultrasound signal backscattered from red blood cells.

- The frequency of the reflected ultrasound wave increases or decreases according to the direction of blood flow in relation to the transducer.
  
  Types:
  - CW Doppler
  - PW Doppler
Beamforming: Adjusting pulse delays to focus the beam at a certain region in the body
Ultrasound Front End Unit Block Diagram

High Voltage from Power Supply Unit

1. Transducer
2. Current Sensing
3. Window Comparator
4. ADC
5. REF
6. TX MUX DEMUX
7. HV MUX DEMUX
8. T/R Switch
9. Integrated Digital Pulsar
10. Linear Amp
11. DAC
12. REF
13. +100V +5V
14. -100V -5V
15. Pwr FETs
16. HV Driver
17. Level Shift
18. AMP
19. Time Gain Control
20. DAC
21. REF
22. Temp Sensor
23. REF
24. REF
25. REF
26. CW Signal Conditioning
27. CW Doppler
28. Analog Beamformer
29. ADC
30. AMP
31. To Spectral Doppler DSP & Audio
32. TX & RX AFEs, Beamformers, Power Supply Sync

Front-End Power Supply

1. 12V Power Bus from Power Supply Unit
2. 5V, 3.3V, 1.8V & 1.2V
3. AFE Low-Noise LDO Power Supply
4. CLK
5. Efuse
6. 12V
7. Sequencer
8. 12V
9. TX & RX AFEs, Beamformers, Power Supply Sync

Front-End Clocking

1. Clock Generation
2. Clock Distribution

Integrated RX AFE

1. LNA
2. VCA
3. PGA
4. ADC
5. REF

Integrated TX AFE

1. T/R Switch
2. TX Beamformers (FPGA)
3. Beamformer Control Unit (FPGA)
4. To Back-end DSP

Texas Instruments
Continuous-wave (CW) Beamformer

In Medical Ultrasound Systems, in the CW Doppler mode the received signals are passed through the CW mixer of the receive AFEs to demodulate the Doppler frequencies and produce I and Q signals. The output of all the AFEs are summed, filtered and amplified before digitizing.

Integrated Receive AFE

Block Diagram of CW Path

8 * fcw and 4 * fcw block diagram
Signal Acquisition system using TI’s High Resolution SAR Converters
Block Diagram – TIDA-01351

AFE × n

Summing Network (Passive R&C)

Summing RC Network

Inphase (I)

Quadrature (Q)

AMP

ADC

AMP

ADC

SAR ADC (ADS8900B * 2)

Summing amplifier, Active filter & ADC Driver (THS4551 * 2)

TPS7A88

5V3_AVDD

3V3_DVDD

REF5050

Data Capture Card

+5V IN
Features of proposed solution

System Solution: This is a data acquisition systems used to process differential I and Q analog signals, with some gain, anti-aliasing filtering. To make it commercially viable, cost reduction by implementations of 16 bit and 18 bit SAR ADCs are also demonstrated.

- Raw Data not available: Usually, there is no provision to have raw data as output. Data is available as oversampled data or it is available as digitally filtered data.

With this TI design, raw data is available for post processing. This has zero latency and have high linearity. SAR ADC’s SNR and ENOB can be improved with oversampling.

- Quantity of components Used: Usually several stages with multiple components are used for low pass filtering the I and Q AFE output signals, anti-aliasing filter, amplifying and driving the ADC.

With this TI Design single stage achieves eight channel summing, filtering, buffering and amplification.

In our app note we describe:

Non-Adaptive filtering: Filtering is done to achieve anti-aliasing and to have cut off for frequencies of the required audio range (eg, 20Hz to 20KHz). Typically implemented using an active high pass and an active low pass filter. Computer controlled MUXs are used to switch the resistor values of the low pass filter to vary the cut off frequencies. By using this method, only discrete values of cut off frequencies are achieved.

We have implemented adaptive low pass filtering circuit. By using a dc controlled voltage, this circuit achieves continuous variable cut off frequency over a large range of frequencies. This circuit also has a large signal handling capacity of 3Vp-p.

Improving the resolution of SAR ADC: Improving the resolution of SAR ADC by oversampling and decimation
Features of proposed solution Continued

Features:

• Two Simultaneous Channels (I and Q) Fully-Differential Signal Chain Providing Zero-Latency True Raw Data With SNR of 101.2dB and ENOB of 16.45

• Designed Using ADS89x0B (20-/18-/16-Bit) With SNR of 104.5-dB SNR and THD -125dB

• For overall lower system cost, implementations of 16 bit and 18 bit SAR ADCs are also demonstrated

• For ultrasound systems having current output AFEs methods to couple 128 channels from AFEs to the differential amplifier demonstration

• Adaptive low pass filtering - A low pass anti-aliasing filter whose cut off frequency can be controlled through a dc voltage
TIDA-01351 – Summing Stage, Active Filter, ADC Driver, Charge Kickback Filter and Analog to Digital Converter

Driver and ADC for I Channel

Driver and ADC for Q Channel
Test Results – ADC Sensitivity Measured With 10uVp-p Input Signal at 2 KHz
Test Results - ADC Performance at 2-kHz Input With Gain of 1

SNR : 101.2dB
ENOB: 16.45 at 1MSPS
Test Results - ADC AC Performance With a Gain of 10 at 2 kHz

SNR : 94.8 dB
ENOB: 15.44 at 1MSPS
Test Results - Time Domain Display of I and Q Signals at 20 kHz
Precision Summing Circuit Supporting High Output Current From Multiple AFEs in Ultrasound Application
Block Diagram - Summing Circuit Supporting High Output Current From Multiple AFES
TINA Simulation for Circuit Using Buffer to Improve the Output Current Sink/Source Capability of THS4130
Output Waveform for Circuit Using Buffer
Noise Analysis and Frequency Response
Adaptive Low Pass Filtering
Introduction – DC Controlled Low Pass Filter

- In Medical Ultrasound Systems, in the CW Doppler mode the received signals are passed through the CW mixer of the receive AFEs to demodulate the doppler frequencies and produce I and Q signals. The output of all the AFEs are summed, filtered and amplified before digitizing.

- Filtering is done to achieve anti-aliasing and to have cut off for frequencies of the required audio range (e.g., 20Hz to 20KHz).

- Typically implemented using an active high pass and an active low pass filter. Computer controlled MUXs are used to switch the resistor values of the low pass filter to vary the cut off frequencies. By using this method, only discrete values of cut off frequencies are achieved.

- Adjacent Applications: Medical Ultrasound in CW doppler, DC controlled anti aliasing filter included in front end of a precision ADC, General purpose DC controllable filter.
Solution

- By using a dc controlled voltage, this circuit achieves continuous variable cut off frequency over a large range of frequencies. In the existing solution, computer controlled MUXs are used to switch the resistor values of the low pass filter to vary the cut off frequencies. By using this method, only discrete values (for eg, by using a four channel mux only four discrete values of cut off frequencies are achieved) of cut off frequencies are achieved. This circuit also has a large signal handling capacity of 3Vp-p. Low value, 30pf variable capacitor is good for RF application.

- **Need for variable cut off frequency:**
  - By varying the cut off frequency of the anti aliasing circuit used before the SAR ADC, we can vary the performance in terms of ENOB, SNR of the digitized signal. Refer to the TI app note on improving the resolution of SAR ADC (sloa240) for more details: http://www.ti.com/lit/an/sloa249/sloa249.pdf
  
  - In many applications, there is a requirement of continuous variable cut off frequency for low pass filter, with this circuit along with differential amplifier can make a variable cut off frequency high pass filter also.
  
  - It can be used in audio frequency range unlike the other methods use varactor diode which is used for higher frequencies.
Refer to the application note on dc controlled low pass filter for circuit description: http://www.ti.com/lit/an/sloa240/sloa240.pdf
Board Test Results

<table>
<thead>
<tr>
<th>Vcontrol (Volts)</th>
<th>Cut off frequency (KHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.39</td>
</tr>
<tr>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>5.88</td>
</tr>
<tr>
<td>4</td>
<td>7.42</td>
</tr>
<tr>
<td>5</td>
<td>12.7</td>
</tr>
<tr>
<td>6</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Result: With $V_{control} = 1V$, $F_{cutoff} = 4.4$KHz

Result: With $V_{control} = 6V$, $F_{cutoff} = 21$KHz
Improving the Resolution of SAR ADC
Oversampling and Decimation Improves Resolution

Frequency Spectrum of ADC oversampled K times

Digital Filtering to Reduce the Noise After Oversampling
Oversampling and Decimation Improves Resolution Continued

<table>
<thead>
<tr>
<th>ADC Parameters</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENOB</td>
<td>17</td>
</tr>
<tr>
<td>BITS</td>
<td>20</td>
</tr>
<tr>
<td>SNR</td>
<td>104.5 dB</td>
</tr>
</tbody>
</table>

SAR ADC Parameters with Operating Frequency of 100KHz – Without Oversampling

<table>
<thead>
<tr>
<th>ADC Parameters</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENOB</td>
<td>18.1</td>
</tr>
<tr>
<td>BITS</td>
<td>20</td>
</tr>
<tr>
<td>SNR</td>
<td>111.13 dB</td>
</tr>
</tbody>
</table>

SAR ADC Parameters with Operating Frequency of 100KHz – With Oversampling and Decimation
High-Resolution, High-SNR True Raw Data Conversion Reference Design for Ultrasound CW Doppler

TIDA-01351

Features

- Two Simultaneous Channels (I and Q) Fully-Differential Signal Chain Providing Zero-Latency True Raw Data With SNR of 101.2dB and ENOB of 16.45
- 8-Channel Summing, Filtering, Buffering, and Gain Implemented in Single-Stage High-Bandwidth, Low-Power, Low-Noise, Single Supply Fully-Differential Amplifier (THS4551)
- High Sampling Rate of 1 MSPS Allows Flexibility in Post-Processing to Improve SNR and Resolution
- Bandpass Filtering for Frequency Range of 50 Hz to 20 kHz
- Operates from Single 6-V Power Supply With Total Power Consumption of 258 mW
- Designed Using 20-bit, 1-MSPS SAR ADC (ADS8900B) With SNR of 104.5dB and THD -125dB

Benefits

- Compact form factor (12cm x 8.5cm area), ideal for portable ultrasound scanners
- Optimized for lowest distortion for excellent audio signal
- Lower noise and particularly much lower 1/f corner helps improving the SNR
- Better matching of I & Q signals in-terms of components and performance

Target Applications

- Medical Ultrasound Application
- Industrial Imaging
- SONAR Imaging Equipment

Tools & Resources

- TIDA-0xxxx Tools Folder
  - Design Guide
  - Design Files
- Device Datasheets:
  - ADS8900B
  - THS4551
  - LDO
A 20-bit Isolated Data Acquisition Reference Design Optimizing Jitter for Max SNR and Sample Rate - **TIDA-01035**

### Features

- Designed to optimize jitter across isolation boundary for maximum signal chain SNR performance and sample rate performance
- 20-bit, 1 Msps, fully differential SAR ADC with integrated reference buffer – ADS8900B
- Isolator propagation delay compensation using Source-Synchronous SPI mode
- Highlights TI’s multiSPI™ digital interface with 1,2,4 SDO lines for high speed MCU/FPGA interfaces
- Low EMI Isolated Power Supply - SN6501
- Host Interface - Precision Host Interface (PHI) Controller

### Benefits

- Complete isolated high resolution, high speed analog DAQ
- Significantly improved SNR for high input signal frequencies
- Maximized SPI data throughput
- Modular system solution

### Target Applications

- Modular DAQ Systems
- Lab Instrumentation and Field Instrumentation
- Design Validation and Verification
- Remote Process Monitoring and Control

### Tools & Resources

- ADS8900B, THS4551, REF5050, OPA376, LMK61E2, ISO7840, ISO7842
- ISO1541D, SN6501, SN74AHC1G04, SN74AUP1G80, LMK14203TZ-ADJ
- TPS7A4700RGWR, TPS709XXDBVT, SN65LVDS4RSET

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20-bit, 1-MSPS Isolator Optimized Data Acquisition Reference Design Maximizing SNR and Sample Rate - TIDA-01037

Features
- Designed to optimize signal chain SNR and sample clock performance across isolation boundary by utilizing two different high performance isolators
- 20-bit, 1-MSPS, fully differential SAR ADC with integrated reference buffer - ADS8900B
- Provides isolation selection table to optimize component choice for multiple channels
- Isolator propagation delay compensation using Source-Synchronous SPI mode
- Highlights TI’s multiSPI™ digital interface with 1,2,4 SDO line capability
- Low EMI Isolated Power Supply - SN6501
- Host Interface - Precision Host Interface (PHI) Controller

Benefits
- Complete isolated high resolution, high speed analog DAQ
- Significantly improved SNR for high input signal frequencies
- Maximized SPI data throughput
- Modular system solution

Target Applications
- Modular DAQ Systems
- Lab Instrumentation and Field Instrumentation
- Design Validation and Verification
- Remote Process Monitoring and Control

Tools & Resources
- ISO7840, ISO7842, ADS8900B, THS4551, REF5050, OPA376, LMK61E2, ISO1541D, SN6501, SN74AHC1G04, SN74AUP1G80, LMZ14203TZ-ADJ, TPS7A4700RGWR, TPS709XDBVT, SN65LVDS4RSET
THANK YOU
I Channel - Summing Stage & Bandpass Filter
Q Channel - Summing Stage & Bandpass Filter
I & Q Channel – Driver and ADC