Receive Side of Data Acquisition System for Ultrasound Imaging Applications

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Data Acquisition System for Ultrasound Imaging Applications**, submitted by **Aparna Mohan, EE12B076**, to the Indian Institute of Technology, Madras, for the award of the dual degree of **Bachelor of Technology and Master of Technology** , is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Ultrasound; DAQ; AFE5809, TSW1405, MAX4781; Pre-beamformed data

Access to pre-beamformed data on ultrasound scanners are limited. Hence research in this domain is limited to certain privileged laboratories. In order to access pre-beamformed data, this project showcases a data acquisition system which can acquire data simultaneously from a transducer having 64 array elements. The DAQ system developed consists of a multiplexing circuit which switches 64 channels from the transducer to 8 channels. An array of 8 MAX4781 multiplexers (1:8) are used and the select inputs are given by a Xilinx Spartan XC3S250E FPGA. The channels are read by an analog front-end AFE5809EVM. It is configurable from the PC through a dedicated GUI which can be used to modify the gain etc. The AFE outputs high-speed serialized LVDS data for 8 channels, which is then read and de-serialized by a data capture card, TSW1405EVM, which has on-board memory to store 65536 16-bit samples. The de-serialized LVDS data from TSW1405 is then read by a GUI on PC via USB2.0 interface. The data acquisition on PC side can be programmed using automation DLL by integrating with MATLAB. The package is a low-cost solution to obtain pre-beamformed data from commercial and clinical ultrasound scanners.

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ABBREVIATIONS

FPGA	Field-Programmable Gate Array
MSPS	Million Samples Per Second
DAQ	Data Acquisition System
AFE	Analog Front End
ADC	Analog to Digital Converter
MUX	Multiplexer
PRF	Pulse Repetition Frequency
GUI	Graphical User Interface
HSDC	High Speed Data Converter
PC	Personal Computer
CSV	Comma Separated Values
DLL	Dynamic Link Library

NOTATION

f_m	Maximum center frequency
f_s	Sampling frequency

CHAPTER 1

INTRODUCTION

Sound waves with frequencies higher than upper audible limit of human hearing are commonly called Ultrasound. This limit varies for individuals and is approximately 20 kilohertz (kHz) in adults. Ultrasound devices make use of these waves and operate with frequencies ranging from 20 kHz up to several gigahertz. (Ultrasound - Wikipedia)

The applications of Ultrasound covers a wide variety of domains. It is often used to measure distances, sense proximity, medical imaging, non-destructive testing of structures, detect cracks and failures in materials, cleaning, mixing, accelerate chemical processes etc. Animals like bats use ultrasound for locating prey and navigate between obstacles.

Ultrasound is extensively used in the medical field due to their non-ionizing nature, portability and inexpensiveness. Ultrasonography is widely utilised in a variety of medical specialities such as anaesthesiology, cardiology, gynaecology, ophthalmology etc. Ability to reveal anatomy, dynamic movement of organs and details of blood flow in real time are the key strengths of ultrasound. (Medical Ultrasound - Wikipedia)

1.1 Overview of Ultrasound Imaging System

Medical ultrasound, also known as *diagnostic sonography* or *ultrasonography* is a widely used diagnostic imaging technique that uses high frequency sound waves to characterize tissues based on various acoustic properties like impedance, compression, reflection etc. One of the main advantages is safety as its uses non-ionizing sound waves. Also, the two main bio-effects, cavitation and thermal heating, are studied very well so that the output can be controlled to limit these effects.

A typical ultrasound imaging device has a transducer probe, connected to a processing machine with a screen to display images. The piezoelectric transducer produces ultrasound waves and the reflections from the area of interested is captured back. This data is then processed using several signal processing and image processing techniques and a image rendered on screen for further diagnosis. The entire process happens real-time so that live body parts can be observed.

1.2 DAQ for Ultrasound

A wide variety of commercial ultrasound scanners are available in the market. These include trolley-based machines intended for bedside applications as well as portable devices that are suitable for point-of-care diagnosis. However, these devices are not easily reconfigurable. In order to fit the hardware to physical constraints, they are mostly developed through an embedded system design approach (Basoglu *et al.*, 1998), which takes away the flexibility to modify front-end scanner operations. Hence, experimental investigations on new imaging schemes and algorithms become difficult for researchers as re-prototyping scanners (Trahey *et al.*, 1999).

In order to enable experimental analysis of new ultrasound imaging methods, access to raw ultrasound data at pre-beam formed level is important. The development of a new pre-beamformed data acquisition system (DAQ) that can collect data over 64 array elements is presented in this report.

1.3 Literature Review

In order to support research on new ultrasound imaging methods through experimental analysis, many research groups have been working on devising ultrasound hardware for acquiring raw data from scanner's frontend (Tortoli and Jensen, 2006). Initial versions were add-ons that can be attached to clinical scanners, like the research interfaces available for *Hitachi HiVision* (Shamdasani *et al.*, 2008), *Siemens Antares* (Ashfaq *et al.*, 2006) and *Zonare z.one* scanners (Mo *et al.*, 2007). In the meanwhile, several academic research teams have also designed in-house systems for raw data access (Masotti *et al.*, 2006). The Ultrasonix system (Dickie *et al.*, 2009) was an attempt to develop a raw data access with an open architecture.

But, for these research interfaces, the data sampled after beam-forming are considered as raw ultrasound data. While access to the post-beamformed ultrasound data is important for evaluation of new signal processing methods, it is not enough for studies on modern imaging paradigms that work with the pre-beamformed data of each element on the ultrasound array.

Several pre-beamformed data acquisition systems have been developed to address this need. Add-on tools are available for *Philips Sonos-5500* scanner (Fabian *et al.*, 2001) and as an extension to *Zonare z.one* system (Mo *et al.*, 2008). Few academic laboratories (Jensen *et al.* (2007), Tortoli *et al.* (2009)) have also developed custom solutions, while a commercial platform is also made available by Verasonics (Daigle, 2012). A very similar work has been carried out by Cheung *et al.* (2012), which is capable of acquiring data parallelly from 128 transducer array elements. Another work carried out by Dusa *et al.* (2014) presents a FPGA based 8-channel ultrasound transmitter.

CHAPTER 2

SYSTEM ARCHITECTURE

2.1 Overview

The overall data and control flow diagram for the system is shown in Fig. 2.1. 64 channel data from an ultrasound transducer probe is fed into a multiplexing circuit which output 8 channels. This multiplexers are controlled by a FPGA which changes the select lines so that 8 channel output goes through all 64 channels. These 8 output lines are then read by analog frontend which converts the analog signals to digital LVDS data. But, this data is serialized and hence a high speed data capture card is used to further read it on to a PC. The GUI on PC can be programmed to capture and save data at certain intervals. Data can be saved as ADC codes in CSV format. This data can be later used to do further processing.

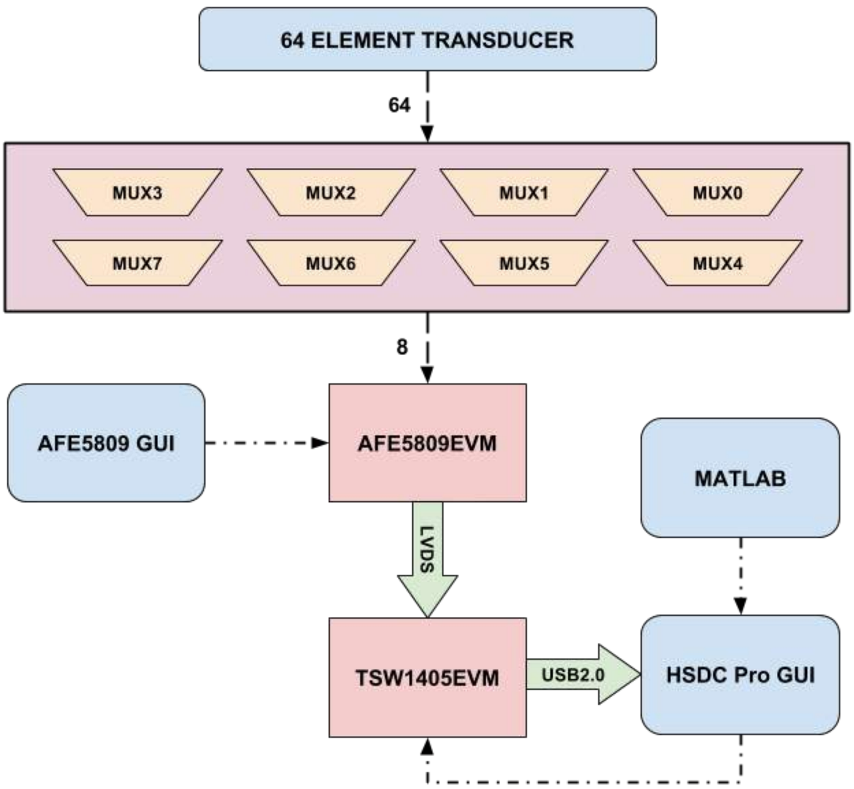

Figure 2.1: Flow diagram for receiver end

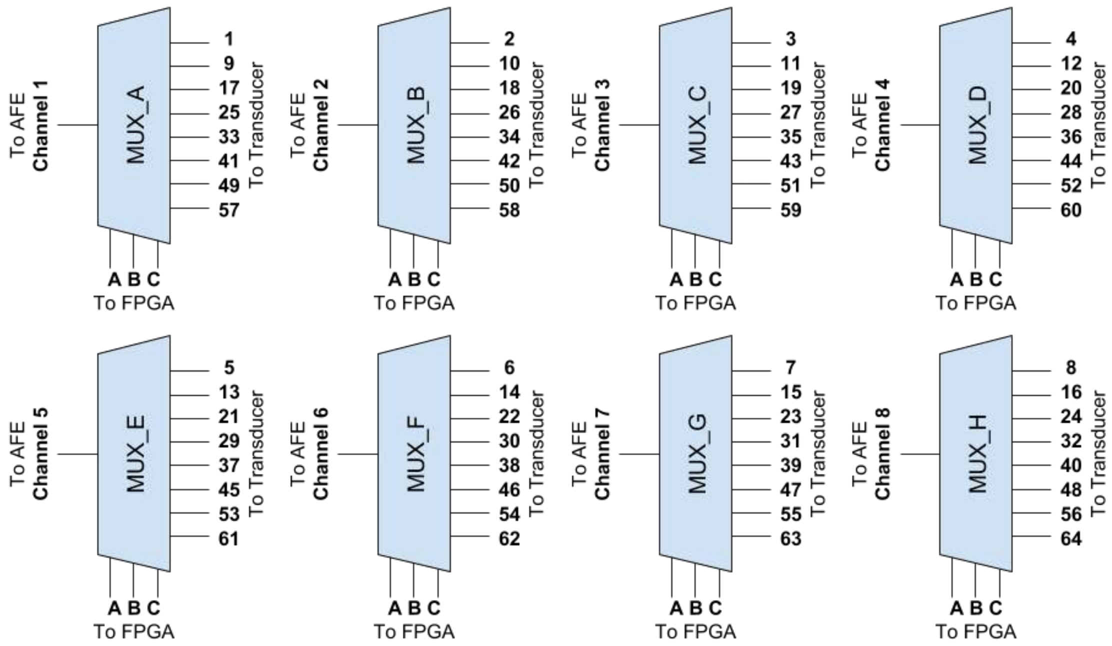

Figure 2.2: Pin diagram for multiplexing circuit

2.2 System Components

2.2.1 Multiplexer

The pre-beamformed data, often called channel-domain data, from transducer has to be processed by the analog front-end (AFE). Since AFE can only acquire data simultaneously from eight channels, hardware capable of spanning through all 64 channels from transducer is required. Multiplexers (MUX) are used to switch between 8 channels each at a time from transducer.

Since the MUX have to operate in high frequencies, various factors like ON channel resistance (R_{ON}), leakage currents, charge injection, cross talk, OFF isolation etc. have to be considered while choosing the appropriate IC. (Tutwiler *et al.*, 1999)

MAX4781[1], a high-speed, low-voltage multiplexer is found to be the best fit for the application. It is a low on-resistance, CMOS analog switch configured as an 8-channel multiplexer. The input signal voltage should lie between $-0.3V$ to $4.6V$.

The three select inputs are provided to the MUX via a Xilinx Spartan XC3S250E FPGA[2] using CoreXC3S250E development board. Verilog code for providing rapid

[1] https://www.maximintegrated.com/en/products/analog/analog-switches-multiplexers/MAX4781.html

[2] https://www.xilinx.com/support/documentation/data_sheets/ds312.pdf

Select			Transducer element at each channel							
A	**B**	**C**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	0	0	1	2	3	4	5	6	7	8
0	0	1	9	10	11	12	13	14	15	16
0	1	0	17	18	19	20	21	22	23	24
0	1	1	25	26	27	28	29	30	31	32
1	0	0	33	34	35	36	37	38	39	40
1	0	1	41	41	43	44	45	46	47	48
1	1	0	49	50	51	52	53	54	55	56
1	1	1	57	58	59	60	61	62	63	64

Table 2.1: Transducer array elements assigned to each channel for every select input to the MUX

switching signals have been simulated and validated using Xilinx ISE and then programmed onto an EEPROM available as a module on the development board. 8 simultaneous channels are chosen at a time by giving the appropriate select inputs for each MUX. Each MUX is connected to the transducer and AFE as shown in Fig. 2.2. The transducer element connected through each channel for each select input is shown in Table 2.1. Hence, for every select input a continuous array of 8 elements are available at the AFE channels. Frequency of changing the input is calculated according the pulse repetition frequency (PRF) of the transmit signal, which is in turn calculated based on the depth of imaging.

Each pulse sent through the ultrasound transducer should be spaced by a time period which is more than the time the signal takes to travel through the depth and come back to the transducer. This frequency is called PRF and the MUX have to be switched to the next set of 8 channels after at-least one pulse have been sent and received back.

2.2.2 Analog Front End

An analog front-end (AFE) contains all the circuitry required to act as an electronics functional block that does analog to digital conversion along with filtering, amplification etc.

Analog to digital converter (ADC) in the AFE used here is AFE5809 from Texas

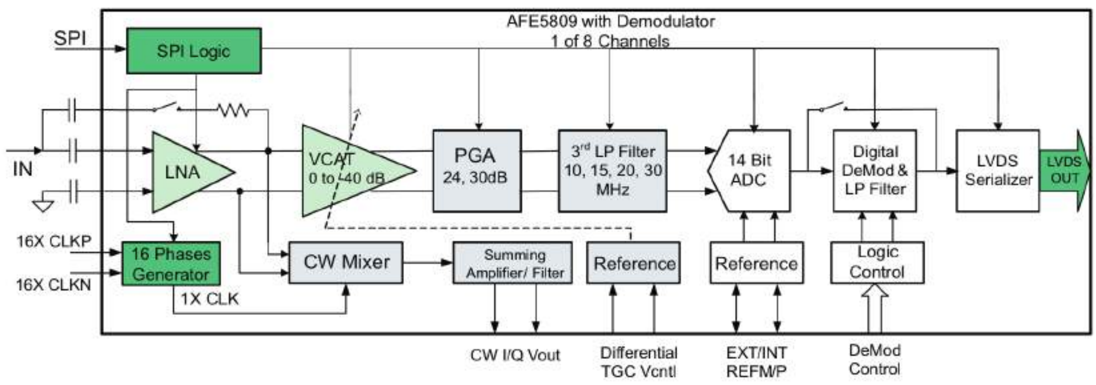

Figure 2.3: Functional block diagram of AFE5809[3]

Instruments. It is an 8-channel AFE specifically designed for ultrasound systems in which high performance and small size are required. The maximum sampling rate is 65 MSPS and it also provide options for selecting various power and noise combinations in order to optimize system performance.

For ultrasound applications, the maximum center frequency of the transducer is 20 MHz. According to Nyquist theorem, a sufficient sampling rate (f_s) is at-least two times the band limit or the maximum center frequency (f_m). i.e.

$$f_s \geq 2 \times f_m \tag{2.1}$$

Hence, an AFE with sampling rate of 40MSPS or greater would suffice for the application, AFE5809 being able to provide 65MSPS with three different options for quantisation levels, 12, 14 or 16 bits. The following signal conditioning occurs within the AFE, as shown in Fig. 2.3.

- 24-, 18-, 12-dB Gain Programmable Low-Noise Amplifier (LNA)
- 40-dB Low-Noise Voltage Controlled Attenuator (VCAT)
- 24-/30-dB Programmable Gain Amplifier (PGA)
- Third-Order Linear Phase Low-Pass Filter (LPF) with 10, 15, 20, 30 MHz frequencies to use with transducers.

For the current application, AFE is operated at 40MHz using internal clock, and hence providing a sampling rate of 40MSPS. AFE is powered using +/-5V external supply and connected to the PC via USB2.0. The AFE5809EVM GUI (Fig. 2.4) is used

[3]http://www.ti.com/lit/ds/symlink/afe5809.pdf

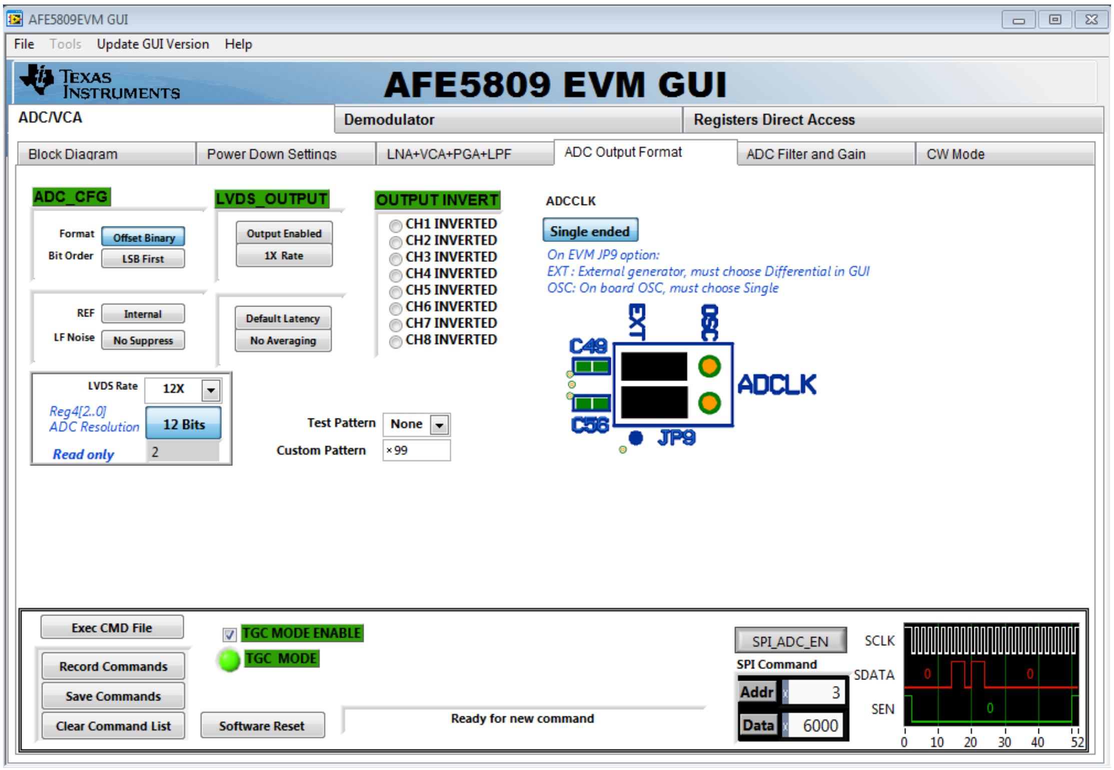

Figure 2.4: GUI Interface for AFE5809EVM

to initialise the board. Upon connecting the GUI, two red LEDs will stop glowing. The settings selected under ADC/VCA ADC Output Format are

- ADC CFG: Bit Order LSB First
- LVDS OUTPUT: 1X Rate
- ADC CLK Single Ended
- LVDS Rate 12X
- ADC Resolution 12 Bits

LVDS

The output of AFE after analog to digital conversion of channel-domain data is in serialized Low-Voltage Differential Signalling (LVDS) format, also known as TIA/EIA-644. Output rate is set as $1\times$, where each ADC channel has one LVDS stream associated with it. LVDS delivers high data rates (from 1 to 3Gbit/s possible) while consuming significantly less power. Using serialized LVDS transmission has multiple advantages as given below.

- Reduced number of output pins thus saving routing space on the board.

Figure 2.5: Functional block diagram of TSW1405[5]

- Reduced power consumption.
- Reduced effects of digital noise coupling to the analog circuit inside AFE5809.

2.2.3 De-Serializing and Storing Data

The LVDS data from AFE cannot be directly read by a PC. It has to be further de-serialized and buffered to transfer to PC, due to the specialized protocol and high data rate. This is accomplished by using TSW1405EVM[4], a low-cost data capture card from Texas Instruments, which has an on-board Lattice ECP3-35 FPGA from Lattice Semiconductor and a memory capacity for storing 65536 samples of 16-bit data. But, TSW1405 can only run in 12-bit mode and hence it can store 87381.33 samples in the on-board memory and can be read using High Speed Data Converter (HSDC) Pro GUI on a PC. It can analyse up-to 8 channels concurrently. The hardware draws power and transmits data over its mini-USB 2.0 connection.

FPGA on TSW1405 is programmed to de-serialize the LVDS data using certain primitives. The de-serialized data is then buffered on to the on-board memory and later read by the PC through a FTDI USB interface. A high level functional block diagram showing the operation of TSW1405 is shown in Fig. 2.5

Each time "Capture" button is pressed on the GUI, data stored in the memory of TSW1405 is read and shown on the screen, as shown in Fig. 2.6. "Save" action can store the waveform as ADC codes in CSV format. These actions to be done on the PC can also be automated by programmatically accessing the DLL for functions of the HSDC Pro, through MATLAB, Python or C++.

[4] http://www.ti.com/tool/TSW1405EVM
[5] http://www.latticesemi.com/en/Solutions/Solutions/SolutionsDetails02/TexasInstrumentsADCDACs.aspx

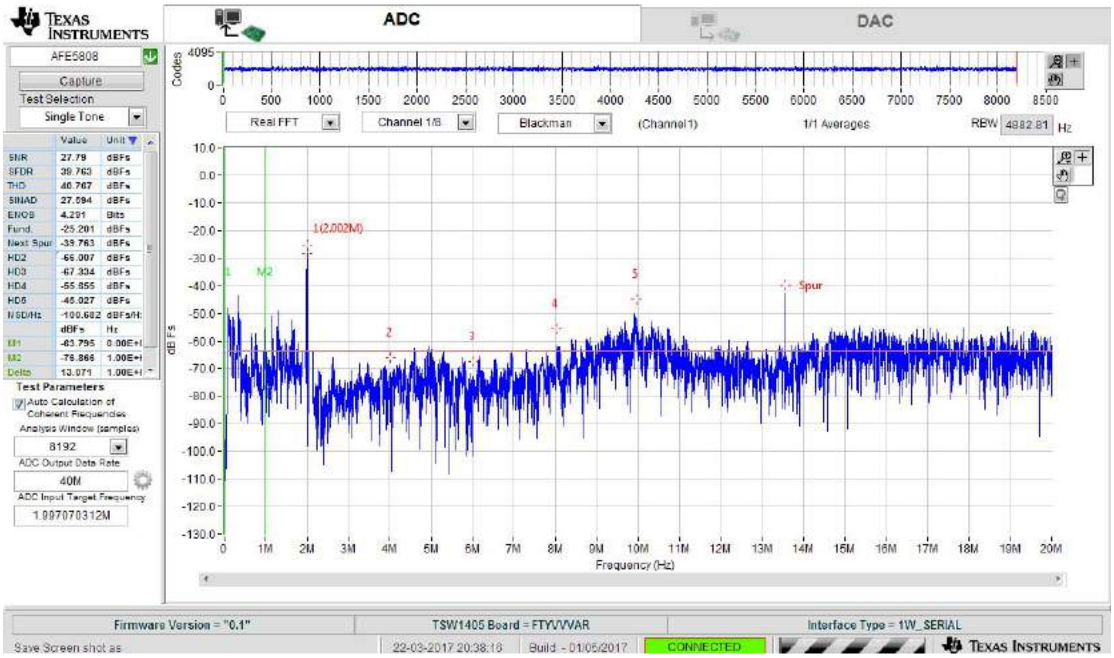

Figure 2.6: Data capture through HSDC Pro GUI

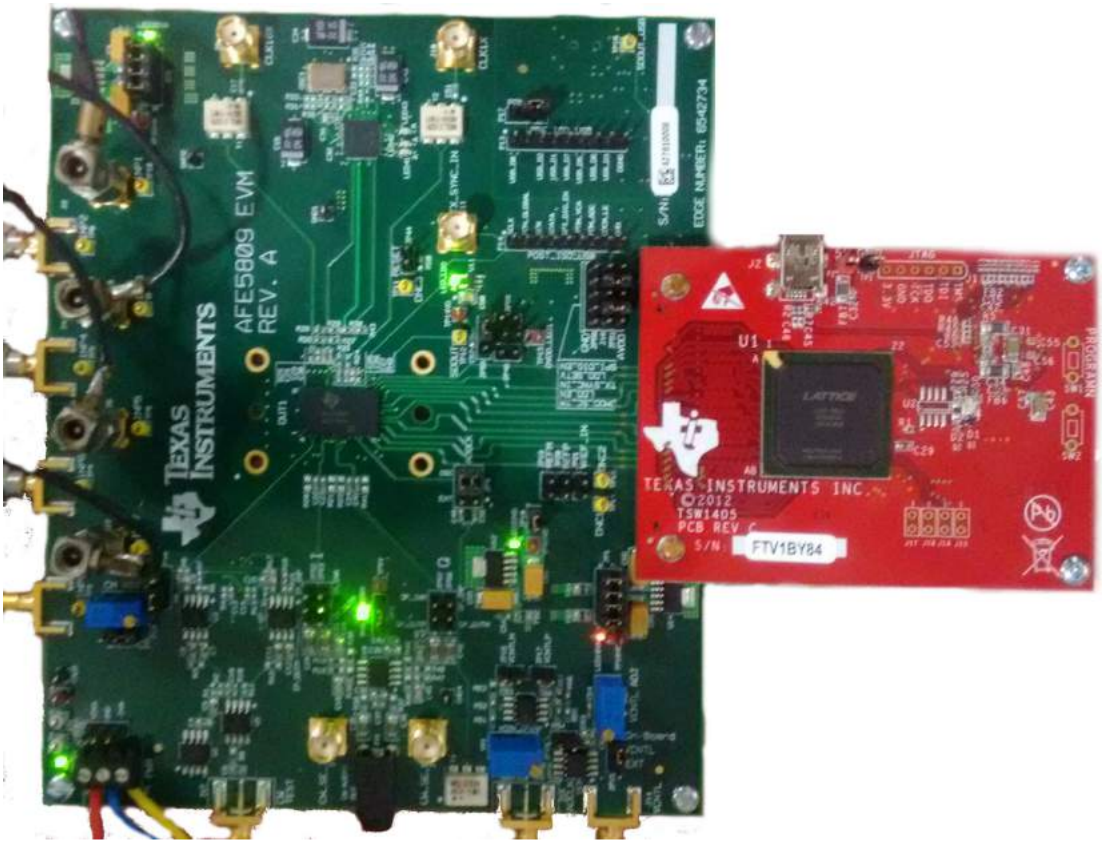

Figure 2.7: AFE5809EVM connected to TSW1405EVM

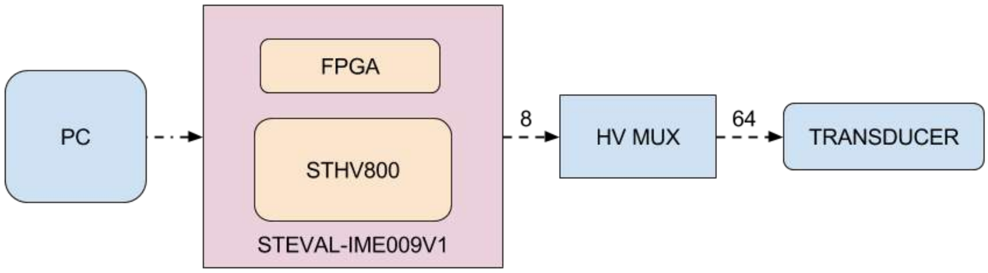

Figure 2.8: Flow diagram for transmit side

The evaluation board is directly connected to the LVDS interface of AFE, through a LVDS connector. Both the boards are shown in Fig. 2.7.

2.2.4 Transmit Side

STHV800 based ultrasound pulser IC evaluation board STEVAL-IME009V1[6] is used for generating waveforms for the transmit side. It has 8 channel high-voltage output, which is connected to the transducer through a high-voltage multiplexer since transducer has 64 elements. A flow digram is shown in Fig 2.8.

[6] `http://www.st.com/en/evaluation-tools/steval-ime009v1.html`

CHAPTER 3

VALIDATION EXPERIMENTS

Two experiments are carried out to verify the validity of the system. Certain samples for which ground truth is known are scanned and the pre-beamformed data is captured using the device. This data is analysed to verify the system.

3.1 Photoacoustic Imaging

Photo-acoustic imaging is a molecular, functional and structural imaging modality. It is based on photo-acoustic effect, where the non-ionising laser pulses delivered to the biological tissue will be absorbed and converted to ultrasonic emission due to localized thermal expansion. In photoacoustic tomography, an array of transducer captures the ultrasonic waves generated on illumination by pulsed Nd:YAG laser at 1064nm. This data can be used to reconstruct image which represents the absorption of light within the phantom. It is used in applications such as brain lesion detection, breast cancer diagnosis etc. The proposed DAQ system is used to acquire experimental data to validate the algorithm for photoacoustic imaging.

3.1.1 Experimental Setup

The experiment is performed using Q-switched, pulsed Nd:YAG Litron laser (LPY 704G, Litron Laser Ltd., Rugby, UK) of 7ns pulse duration at 1064nm wavelength and 1Hz PRF. The complete experimental set up is shown in Fig. 3.1. The laser pulse was made to fall on a 5cm x 5cm x 4cm gelatin phantom that was made with 5% concentration of type-A gelatin derived from acid-cured porcine skin (Sigma-Aldrich Corp., St. Louis, MO). A 0.7mm diameter super polymer lead acts as the PA target and it was embedded at a depth of 2.5cm from the top surface of the phantom where the transducer was placed and at 1.5cm from the front surface where the laser light was directed to. For detection, a 7.5 Mhz ultrasound linear array transducer with 64 elements and 0.22mm

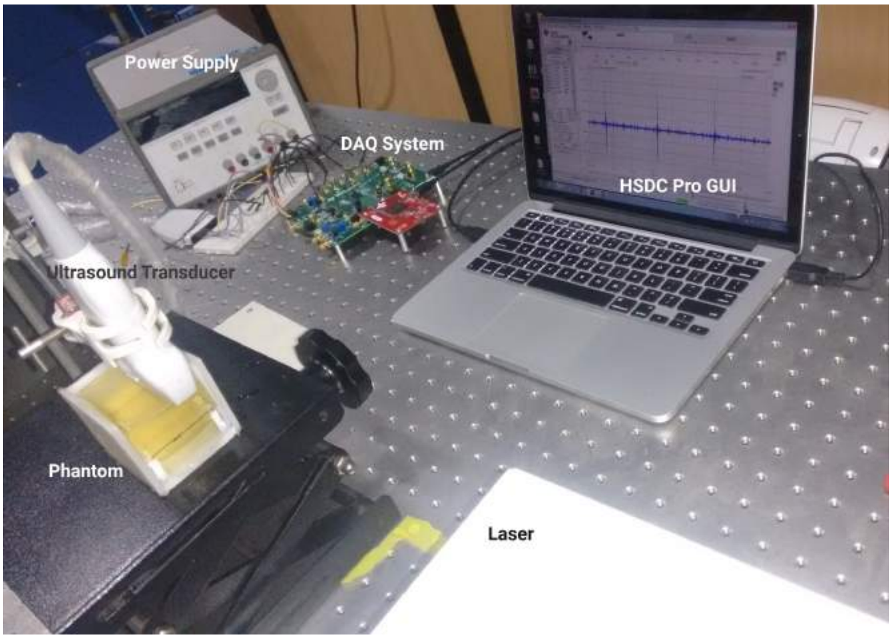

Figure 3.1: Experimental setup for photoacoustic imaging

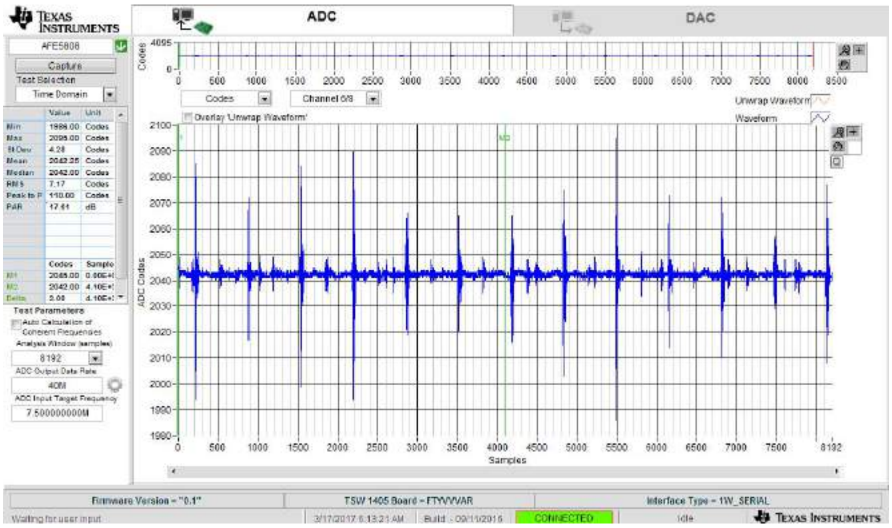

Figure 3.2: Data captured by DAQ for photoacoustic imaging

pitch having an aperture length of approx 14mm was used. The imaging transducer was placed perpendicular to the long axis of the cylindrical lead inclusion in order to effectively capture the spherical waves released along the radial direction, due to thermal expansion caused by the incident laser light.

The pre-beamformed data from ultrasound transducer is then read by the AFE and then transferred to PC through TSW after de-serialization. Data, which is in the form of ADC codes are captured using HSDC Pro GUI. This is used to reconstruct the initial pressure distribution.

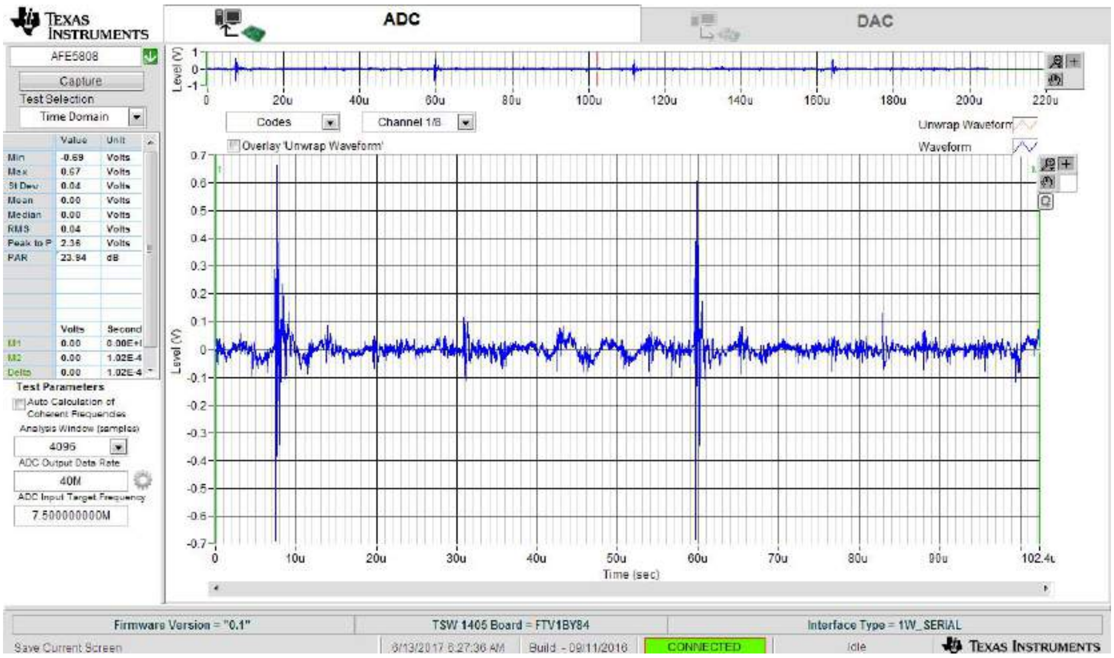

Figure 3.3: Time domain data captured by DAQ

3.2 Ultrasound Imaging

To validate the working of DAQ for a typical ultrasound application, an experiment is set-up to calculate the speed of sound in a previously calibrated phantom. The experiment is to measure time taken for the first reflection from the phantom, so that along with known distance, speed can be calculated.

3.2.1 Experimental Setup

High voltage pluses are given from a pulser in transmit mode to a single element unfocused transducer. A 64 element 7.5MHz transducer is used to passively receive the ultrasound signal from the phantom. Output of transducer is fed into the DAQ system to acquire and store data. The data captured by HSDC Pro GUI is shown in Fig.3.3.

3.2.2 Results

Occlusion is at 2.7 cm (d) and time taken for first reflected signal is 24μs (t). As it is passive receive, speed of sound in the medium, c

$$c = \frac{d}{t} \tag{3.1}$$

$$c = \frac{2.7 \times 10^{-2}m}{24 \times 10^{-6}s} \tag{3.2}$$

$$c = 1125ms^{-1} \tag{3.3}$$

The known value for speed of sound in the phantom is $1200ms^{-1}$. The calculated value, $1125ms^{-1}$ is very near to actual value.

CHAPTER 4

CONCLUSIONS

The DAQ system developed in this project can be used to acquire pre-beamformed ultrasound data, also called as channel-domain data from ultrasound transducers. Coupled with the transmit side circuit, this can be used as a completed ultrasound experimental system.

There are few limitations in the current system. The maximum data rate from the AFE5809 is 40MSPS/channel or 360MSPS for 8 channels. The data rate for 12bit samples on all 8 channels would be 480MBps. Hence, TSW1405 is receiving 480MBps through LVDS. But, it can only store 65536 samples of 16bit data, i.e. approximately 1MB. That means 480 memory rewrites happens in 1 second on TSW1405. Now, the PC has to read at least 480MBps in order to obtain all the samples, in 480 separate reads, since buffer is only 1 MB. But the data rate provided by PC to TSW is only 60MBps, since it is USB2.0. Therefore, unless more memory buffer is provided in LVDS de-serializer, data is bound to be lost.

CHAPTER 5

FUTURE WORK

The transmit side can be implemented based on the specifications discussed in the report. Various transmit beam-forming algorithms can be implemented and multiplexed to all 64 channels of the transducer. The system will then function as a complete data acquisition system.

Also, a dedicated system for the output from ADC can be realized. This can be preferably implemented by replacing TSW1405 with a custom FPGA coupled with larger on-board memory. This would make the system faster as it can be modelled for specific requirements. The raw RF data captured can be processed within the FPGA by implementing the receive beam-forming to make an integrated system. The can be transferred to the PC in order to visualise the image relatively in real time.

Characterization of the designed system can be done. All the options available in the AFE GUI, as well as SPI programming to change the values in registers in the AFE can be explored.

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