Jurnal
Teknologi

Full paper

Study and Design of an Ultrasonic Flow Tomographic Front-End Multi Level Measurement System

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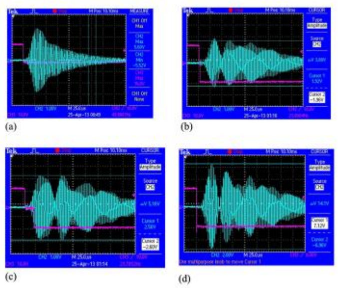
Article history

Received :12 Februari 2014
Received in revised form :
1 April 2014
Accepted :25 July 2014

Graphical abstract



Abstract

With the rapid evolution of electro-acoustical technology, ultrasonic tomography has made considerable progress in industry. An ultrasonic tomography system provides non-invasive and non-intrusive flow visualisation that enhances the understanding of fluid flow processes. The function of ultrasonic tomography is to continuously monitor the dynamics of liquid flow without interrupting the flow. The ultrasonic tomography technique is fully supported by a front-end hardware system. The front end is defined as all the hardware circuitries, including the ultrasonic transducer up to the Analogue-to-Digital Convertors (ADCs), even though the primary focus is the analogue signal processing components. We present here the challenges and trade-offs in the implementation of a front-end system by first explaining the basic operation of such a system, and then indicating what particular performance parameters are needed to ensure optimal system operation. Based on the results from our research studies, we propose an improved front-end multi-level solution that is more accurate than previous solutions and provides real-time measurement capability.

Keywords: Ultrasonic transducer; tomography; ADC; multi-level pulser; operational amplifier

■1.0 INTRODUCTION

An ultrasonic transmitter operates by sending electrical signals to the surface electrode of the transducer. The crystal of the transducer is polarized, and it pulses the transducer to emit ultrasonic beam through the sensor wall. The ultrasonic beam (or the mechanical distortion) is generated according to transducer's voltage and center frequency. When the transducer acts as a receiver, the ultrasonic sound, in the form of a returning echo or vibration pressure pulses, impacts the crystal, and this vibration results in the production of electrical energy. The application of an ultrasonic transducer in medical imaging systems has a long history; the first paper on medical ultrasonic technology was published in 1942 by Doctor Karl Theodore Dussik of Austria [1] and since then, medical ultrasonic technology has expanded and has been used in many ways, including examining the health of unborn babies, analyzing bone structure, and tumor screening.

Regarding industrial application, the use of ultrasonic transducers in flow meters was first introduced in 1963 [2].In existing technology, commercial flow meter uses 1 pair of transducers for velocity measurement. A single-path ultrasonic meter calculates flow rate based on a single path through the pipe, making it quite susceptible to flow profile. Multipath flow meters are more accurate since they use multiple paths to make the flow calculation [3]. Measuring techniques with the capability of continuously monitoring the dynamics of the liquid flow without interrupting the flow conditions is required to elucidate the transient phenomena in flow systems. The ultrasonic tomography technique enables non-invasive and non-intrusive flow visualisation, regardless of the material opacity, which enhances the understanding of such complex fluid flow processes. With the rapid evolution of ultrasonic technology, ultrasonic transducers are recognised as one of the ideal process sensor technologies, and ultrasonic flow meters are anticipated to be in high demand in future industrial flow applications. Ultrasonic flow meters have been researched recently in fluid-flow industrial processes, which have enabled interior flow image monitoring; the use of such flow meters in closed-loop industrial control systems will be a key element in future industrial flow processes. As reported by RichardTweedie [4], there has been significant interest in the use of ultrasonic transducers for use in the various characterisations of materials, such as in the measurement of the density of solids and of pure/mixed liquids, the determination of the thermal properties of liquids, the rheological characterisation of liquids and soft solids through determining the phase velocity, the particle sizing of colloids using attenuation, and the measurement of relaxation phenomena in biomaterials and soft solids.

For the purpose of constructing a slice of image in a flow regime, arrays of sensors need to be distributary mounted onto the curvilinear of the pipeline. The sensors arrangement is termed as sensor modality. Single modality is sensors arrangement using a same type of sensors' technology. In the ultrasonic single modality, a fan-shaped beam sensor array is primary the configuration of sensor arrangement. The analogue outputs of sensor array are fed into front-end hardware system. The front end is defined as all the hardware circuitries, including the ultrasonic beam formers up to the Analogue-to-Digital Convertors (ADCs) even though the primary focus is on the analogue signal processing components. The front end in an ultrasonic flow system always refers to the transducer arrays and associated electronic hardware to acquire the sensor data. Electronic designers must understand the ultrasonic flow system specifications and the relevant considerations as well as their effect on system performance because the awareness of these design challenges will help designers to achieve the most advantageous system design. In this paper, we first present in section 2 a detailed description of the design challenges in ultrasound systems. In section 3, we provide a contemporary view on front-end system fundamentals based on the previous works of other researchers. In section 4, we present our improved front-end solution, and experimental results. Finally, we conclude our work.

2.0 CHALLENGES OF FLOW SYSTEM

In the ultrasonic flow measurements system, the fixture jig with ultrasonic transducers is clamped at the outer layer of the flow region, and the flow measurements are performed outside of the pipeline. Figure 1 shows the typical ultrasonic fan-beam flow rig design [5] applied by recent ultrasonic tomography researchers. In the fan-beam flow system, ultrasonic transducers act as either a transmitter or receivers. Each projection cycle, one of the transducers will act as transmitter; whereas the rest of sensors will be receivers. In the sensor single modality of Figure 1, the total projection cycles is 32 as total number of ultrasonic transducers being mounted on the investigated pipeline.

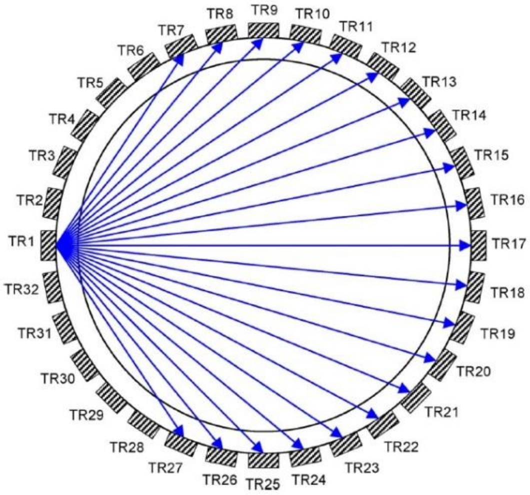


Figure 1 Typical fan-beam flow system

Two basic quantities are measured in ultrasonic flow systems: the time-of-flight (or the amount of time for the sound to travel through the sample) and the amplitude of the received signal [2]. It is important to know what the ultrasonic flow imaging modality is going to achieve in order to have right understanding on the challenges in ultrasound and the impact on the front-end circuitry design. First, the target of the ultrasonic flow imaging system is to give an accurate representation of the flow inside the investigated pipeline. Second, through signal display processing, the movement inside the pipe is determined, e.g., fluid flow or oil/gas/water flow mixtures.

The first challenge in ultrasonic flow systems is that an ultrasonic transducer generates not only a single frequency but a range of frequencies around the centre frequency. This broadband character is in part due to the fact that the crystal inside the ultrasonic transducer continues to generate some ultrasound output even after the electrical signal has been terminated, the so-called "ringing" effect. Another challenge is the large acoustic impedance mismatch between the transducer elements and the body of the investigated medium. The acoustic impedance mismatch requires matching layers inside the body of the transducer to enable high efficiency of energy transmission. The impedance matching normally consists of a couple of matching layers in front of the transducer elements. A rubber silicone matching layer is commonly used in ultrasonic transducers for an air-borne medium, while an immersion-type matching layer is used for a water medium. The acoustic impedance is minimised by applying a coupling gel, which enables good contact of the transducer with the investigated body.

In all imaging systems, ultrasonic transducers are connected to the front-end circuitry at the end of relatively low-noise cables, which, for most systems, consist of micro-coaxial or RF cables, with the number of cables ranging from 4 to 256 cables. The cables are one of the most expensive parts of an ultrasonic flow system. Due to the cable mismatch with the loading of the cable capacitance on the transducer elements, the system is expected to exhibit a significant signal loss on the order of 1-3 dB, depending on the transducer and its operating frequency. The higher the frequency, the higher the loss incurred as crosstalk of the signal. Thus, the receiver noise figure is lower by the amount of the cable loss. In addition to the cable loss, the high-voltage transmit/receive (T/R) switches that are normally used in an ultrasonic system are mechanical relays that introduce large parasite capacitance in addition to that of the cable. Due to the signal noise sources, the large dynamic range of the receiver represents the most severe challenge. The front-end circuitry must have low noise and large signal handling capability. If the loss of the cable and the switching noise at the ultrasonic frequency is 2 dB, then the noise figure is degraded by 2 dB, i.e., the first amplifier after the switch must have a noise figure that is 2 dB lower than that required with a lossless cable. Dynamic ranges of this power magnitude are not easy to directly achieve. Therefore, the front-end circuitry of an ultrasonic system is always a highly sophisticated system, the design of which involves a trade-off between the penetration depth and the image resolution, which high penetration depth requests higher transmit power, and better image resolution with higher ultrasound frequency [6].

Another important challenge for an ultrasonic imaging system is fast overload recovery. In addition to switching the transducer function between transmitter and receiver, the T/R switch protects the receiver from high voltage. However, a small fraction of high voltage leakage across the switches can overload the entire front-end system. Poor overload recovery can cause the receiver to stop functioning, and until it recovers, the ultrasonic imaging system will suffer from missing image information. The sampling rate of an ultrasonic flow imaging system is also a major challenge for the design of a front-end system. Sampling is the process of converting an analogue signal into a numeric sequence. In the front-end system, the analogue-to-digital converter (ADC) digitises the signals into numeric information that can be used for further display processing. In principle, based on the Nyquist theorem, the sampling rate of an analogue system must be at least two times the centre frequency. The Nyquist theorem states that a signal must be sampled at least twice as fast as the bandwidth of the signal to accurately reconstruct the waveform; otherwise, the high frequency content of the signal will alias at a frequency inside the spectrum of interest. An alias is a false lower frequency element that appears in sampled data that is acquired at too low a sampling rate [7]. The front-end system must be a highly oversampled system because a large number of high performance phased-array ultrasonic transducers are typically implemented in an ultrasonic flow imaging system. A real time or instantaneous display of an ultrasonic image system is only possible with the availability of a fast sampling rate for acquiring accurate signal and for reducing the acquisition time of the overall system.

■3.0 FRONT-END SYSTEM DESIGN

The front-end electronic system is the first phase of the ultrasound tomographic process to generate and collect the basic measurements though the ultrasonic sensors mounted on the investigated flow region. This first phase requires a significant amount of electronic circuitry design and analysis to produce stable and reliable signal excitation and acquisition. In ultrasound system front-ends, the analogue signal processing components are key elements in determining the overall system performance; once noise and distortion have been introduced in the front-end phase, it is impossible to remove them at a later phase using software processing. This noise issue is a general problem in any receives signal-processing chain.

In 2010, Mohd Hafiz Fazalul Rahiman *et al.* used a low-voltage ultrasonic transducer as the core of an ultrasonic flow imaging system in their design strategy for a system suitable for use in a small-scale plant [5].A tone burst of a 333 kHz sound wave with repetition frequency of 150 Hz produced by the front-end system was verified to be long enough for transient effects but short enough for the burst to be received without multiple reflections. In the ultrasound receiving circuitry, operational amplifiers with sample and hold electronic circuitries were the key elements; the operational amplifier circuits amplified the received signals. The received signals were found to be slightly distorted due to the transit of the ultrasound signals though several layers of inhomogeneous media (acrylic-liquid-acrylic). The sample-and-hold operation was introduced in their system to discriminate the exact information based on the expected time of flight. The system captured and held a signal at a specific point in time, and these stored signals provided the amplitude information for the purpose of image reconstruction. Similar to above front-end design strategy, Hudabiyah *et al*. [8] discussed the details of a front-end system for the investigation of multiphase flow. The investigated flows included flows in the solid, gas and liquid phase in 100 mm pipelines. In their research, 16 transceivers were arranged in a fan beam configuration mode at the periphery of the acrylic pipeline, and their results demonstrated that the developed front-end ultrasonic system was able to obtain data with high accuracy; in their research, using the operational amplifier and peak detector at the front-end system, the measurement of the amplitude of the received ultrasonic signal was improved. Figure 2 shows above mentioned simplified diagram of an ultrasonic flow imaging system.

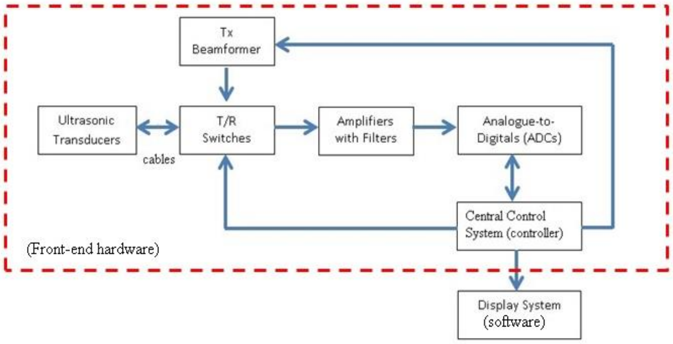


Figure 2 Simplified block diagram of ultrasonic tomographic system

An ultrasonic transducer acts as either a transmitter or receiver, with the functionality selected via a TR switch. After a certain distance of sound travelling through the investigated pipeline, the ultrasound signals detected at the receive path amplifier side is normally a very weak signal in micro voltage (μV range). Thus, the design of the receiving circuitry must be able to process a small signal, which requires blockage at the switch to prevent high voltage from entering into the receiver circuitry. This leakage will potentially destroy the receiver circuitry. The TR switch is generally formed by a diode bridge, which has the capability to isolate and protect the high voltage transmit pulses from entering into receiver circuitry during the receive interval. In a fast switching ultrasonic flow imaging front-end, the TR switch must have fast recovery times to ensure that the receiver can be turned on immediately after sending a transmit pulse. A TR switch must be able to switch rapidly to quickly modify the configuration of the active transducer's aperture and to maximise the image frame rate. In addition, TR switches must have minimal charge injection to avoid spurious transmissions and their associated image artefacts. The MAX319 analogue switch, acting as a TR switch, allows independent control of each channel through a digital control signal. MAX319 is a single pole double-throw (SPDT) switch that has a fast switching time in the nanosecond (ns) range and its output amplitude is guaranteed to remain constant over the required analogue signal frequency range. The MAX4936 switch is a possible alternative TR switch. MAX4936 has 8 channel TR switches integrated in a single IC based on a diode bridge topology. MAX4936 allows independent control of each channel through a daisy-chained SPI interface, in which only three pins are required from the microcontroller to control any channel in the front-end system [9].

When an ultrasonic transducer acts as a transmitter, a digital transmit (Tx) beam former generates the necessary digital transmit signals with the proper delay pattern and pulses to produce a focused transmit signal. In the above-mentioned previous ultrasonic flow tomography research articles, a microcontroller was used to generate dual-frequency burst tones, for example, in the system based on a dual frequency of 333 kHz and 150 Hz, reported by Hudabiyah Arshad Amar *et al.* [8], the switching on and off of single positive-level pulses were produced using MOSFET elements to form the Tx beam former. Instead of using single level pulses, multilevel voltage pulses can be used in the dual-frequency burst tones for producing the transmit signals. In this alternate implementation of the Tx beam former, highly integrated, high-voltage pulsers can be used to replace the MOSFET technology in their front-end designs for supporting multilevel signals. To generate a simple multilevel bipolar transmit signal, a transmit pulser alternately connects the element to a positive and negative transmit supply voltage controlled by the low digital signal from the microcontroller. The high-voltage pulser of the Tx beam former needs to be designed with a focus on the noise and impedance matching issues because ringing during positive and negative signal transitions will affect the image quality. Based on a simplified circuit implementation, the use of pulsers with integrated circuits allows for more connections to multiple supplies and ground to generate more complex multilevel waveforms with better transmitter characteristics.

In a well-designed front-end system, when ultrasonic transducers act as receivers, the signals received from receivers will be fed to amplifiers with filters circuitry. The low noise amplifiers (LNA) set each channel's performance. The LNA output signals are designed to have at least two stages of amplification (denoted as pre-amplification and amplification) to utilize the full-scale range of the analogue-to-digital converter (ADC) with the return signals. Ultrasound transmission through the medium of interest becomes weaker with the depth of the medium and the travel time. To retrieve the information on the medium, the LNA in the receiver must have excellent noise performance and sufficient gain. It is important for the LNA to have active-input-termination capability to provide the requisite low-input impedance termination and excellent noise performance. After the pre-amplification process, the next stage involves band-pass filtering circuitry using an operational amplifier. The band-pass filter is used to ensure that the small signals are readily discerned by ensuring the signals are not buried in the high close-in noise floor of the amplifier [10]. Recently, advances in integration have allowed system designers to migrate to smaller, lower cost, and more portable imaging solutions with performance approaching an operational amplifier designed system. Today's state-of-the-art front-end ICs have been introduced by IC providers, in which the ultrasonic front-end IC is a highly compact imaging receiver line-up, including the LNA, variable-gain amplifier, and anti-alias band-pass filter. The advantage of the front-end IC compared to the above-mentioned operational amplifier circuitry is that one single front end IC can be used for supporting various center-frequency ultrasonic systems. In other words, one has to adjust the resistance and capacitance values of the designed operational amplifier circuitry to set the desired frequency and bandwidth, while in the front-end IC design, the IC itself can operate well for any frequency within its operational range, with no adjustment needed. However, our study on the off-the-shelf front-end ICs indicates that the output signals of the front-end IC are only up to 1 Vpp differential LVDS output. The 1 Vpp LVDS output of the front-end IC is insufficient to support the fine image reconstruction in an ultrasonic flow system, based on the findings from previous research reports because full-scale analog outputs fed into the ADC circuitry must be in the range of 5 V to ensure fine image reconstruction from the sensor information. The challenge moving forward for front-end ICs to be used in ultrasonic flow imaging systems is to continue to drive the integration of front-end solutions while increasing their voltage performance and diagnostic capabilities.

In the next front-end phase, the signal outputs of the amplifier circuitry are sent into analogue-to-digital converters (ADC) to digitize the signals for further processing by the central processor unit to produce the visualization of the flow information that is sent into the display system. The high rate of sampling spreads the quantization noise [6]. As discussed in section 2, an appropriate sampling rate of at least twice the center frequency of the ultrasonic beam has to be implemented in the ADC circuitry for signal accuracy and real-time implementation of the front-end system. In the ultrasonic front-end system designs, there are three basic practices in designing the ADC circuitry of a front-end system. Figures 3, 4, and 5 shows the basic block diagrams of an Analogue Beam forming (ABF) system, a Digital Beam forming (DBF) system, and a DBF with a sample-and-hold system.

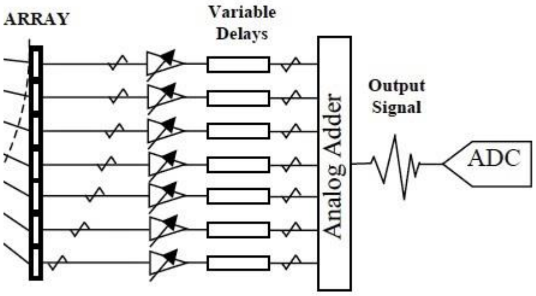


Figure 3 Simplified block diagram of ABF system

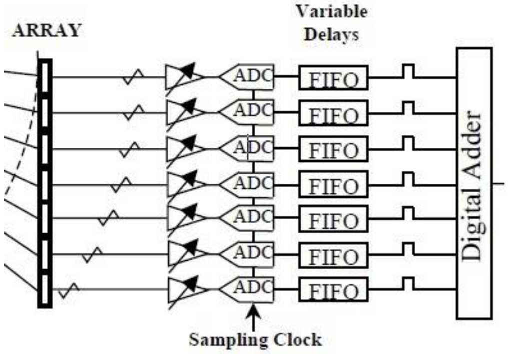


Figure 4 Simplified block diagram of full DBF system

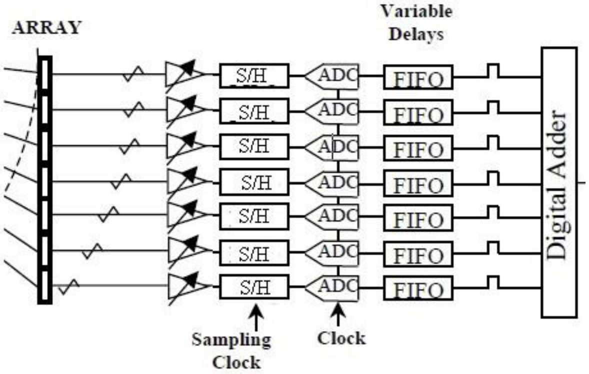


Figure 5 Simplified block diagram of DBF with sample-and-hold

The inputs to the ADC blocks are the analogue outputs of the amplifiers in variable gains. The main difference between an ABF and DBF system are the manner in which the analogue conversion is performed, with both requiring perfect channel-to-channel matching. In an ABF system, an analogue delay line and summation are used, while in a DBF system, the signal is first sampled at a rate as close as possible to at least twice the transducer frequency, and then the signals are delayed and summed digitally. In an ABF imaging system, only one very high resolution and high speed ADC is required, while in a DBF system, 'many' high-speed and high-resolution ADCs are required. To process ultrasonic signals, approximately 60 dB of dynamic range is required, i.e., at least a 10-bit ADC is required. DBF is more popular as the analogue data conversion methodology compared to ABF because the analogue delay lines in ABF tend to be poorly matched channel-to-channel, thus requiring fine adjustment. In addition, an ABF system can only perform differentiation using software. Compared to ABF, digital IC performance continues to improve rapidly, a DBF system with digital storage and summing is "perfect", i.e., no loss occurs once the data had been acquired, which in turn, in the digital domain means that the channel-to-channel matching is perfect. The higher the sampling rate, the finer the reconstructed image as the quantity of data is increased. Ideally, as sample application, with an ultrasound center frequency at 5 MHz, the ADC used in this application is typically a 12-bit device running from 40 mega samples per second (Msps) to 60 Msps to obtain fine delay resolution.

■4.0 EXPERIMENTAL RESULTS AND ANALYSIS

Starting with the above front-end fundamentals, our work involved the improvement of the front end and the detailed front-end circuitry research based on the results from previous research reports. In the following sections, we describe results and detailed descriptions of the operation of ultrasound front-end systems using our improved multi-level front-end design.

The experiments were designed to analyse the influence of multilevel transmit signals in the Tx beam former front-end design. In our experimental set up, a MAX4940 pulser was used to generate multilevel voltages from the low-voltage logic inputs of 3.3 V using a microcontroller. The MAX4940 pulser IC features independent logic inputs, independent high-voltage outputs with active clamps, and independent high-voltage supply inputs. These high-voltage pulsers provide an 8.5 Ω output impedance for the high-voltage outputs and a 21 Ω impedance for the active clamp. The high-voltage outputs can provide 2.0 A (typical) output current [11]. Figure 6 shows the multilevel bipolar Tx beam former circuit design using MAX4940. Block U3_1A shows the voltage supplies; in our experiment, ± 15 V bipolar supplies were implemented. MAX4940 can support 0 to + 220 V Unipolar or ± 110 V Bipolar Supplies. Block U3_1B shows the design with independent logic inputs and quad outputs.

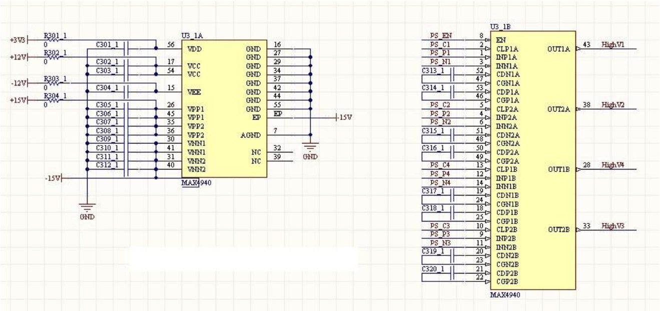


Figure 6 Multilevel beam former circuit

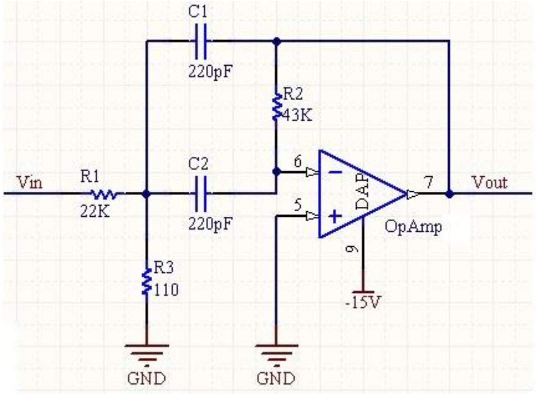


Figure 7 Multiple feedback topology band pass filter circuit

Figure 7 shows the multiple feedback topology (MFB) band pass circuit designed for our ultrasonic flow image front-end system. Capacitors C1 and C2 normally have the same capacitance, *C* value. The MFP band-pass circuit yields the following simplified equations.

$$fm = \frac{1}{2\Pi C}\sqrt{\frac{R1+R3}{R1R2R3}} \qquad (1)$$

$$Am = \frac{R2}{2R1} \qquad (2)$$

$$B = \frac{1}{\Pi R2C} \qquad (3)$$

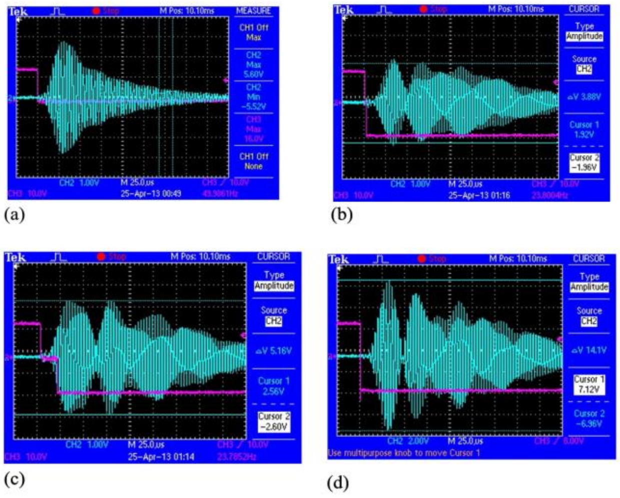
where f_m is the centre frequency, A_m is the gain achieved at the centre frequency, and B is the bandwidth. In an ultrasonic front-end system, the centre frequency refers to the frequency of the ultrasonic transducer, which was 333.3 kHz in our experiment. The gain of the band-pass filter is set to be close to 1 because at this operational amplifier stage, the signal is not yet filtered, so any gain to the input signal will amplify the noise residing in the input signal. The bandwidth of the band-pass filter is set to be as narrow as possible to produce a band-pass signal filter with a narrow bandwidth [11]. Referring to Figure 7, the values of resistance and capacitance in our designed front-end system contribute to the centre frequency, gain and bandwidth of the MFB band-pass filter based on equations (1), (2) and (3) as follows:

$$fm = 333.4kHz \qquad (4)$$

$$Am = 1 \qquad (5)$$

$$B = 33.6kHz \qquad (6)$$

The analysis of the single and multilevel performance of Tx transmit were conducted. The ultrasonic pulse and the received signal are shown in Figure 8. Using the same testing environment in which the same pair of 333 kHz ultrasonic transducer outputs travel the same path length, the multilevel pulses with a full range of ± 15 V without transition delay produced the highest power transmission, which in turn resulted in the highest received signal compared to single-level pulses or the multilevel pulses with internal delay. In the multilevel Tx beam former, sound cancellation occurred.



(a) (b) (c) (d)

Figure 8 Ultrasonic Pulse and Received Signals (CH2 - Received signal, CH3 - Beam former pulse) (a) Single Pulse, (b) Multilevel Pulses, 1us short delay, (c) Multilevel Pulses, 20us short delay, (d) Multilevel Pulses, No delay

From Figures 8(b), (c), and (d), sharp slopes were observed at the initial overlap of two transmission ultrasound signals, in which each positive sound wave cancelled each negative sound wave. In short, the implementation of a multilevel Tx beam former allows for sound cancellation, and this sound cancellation effect can be useful in extracting information from the first arrival of the ultrasound wave after the sound has travelled through the investigated pipeline. Due to the ringing nature of the ultrasonic sensors, there is a tendency to collect irrelevant information at the receiving side; by using this isolation slope, we can filter the relevant information in a more effective way. Figure 9 shows a sample of the zoom-in of the received ultrasound signal. Regardless of the type of excitation Tx beam pulse, the receiving signal was always detected at a frequency of 333.3 kHz, i.e., the same centre frequency generated by the ultrasonic transducer used in our experiments. From the above findings, the design of multilevel pulses in a front-end system can maximise the efficiency of the ultrasonic flow imaging system by increasing the ultrasound transmission power through the investigated medium and by providing higher relevance of the received signal.

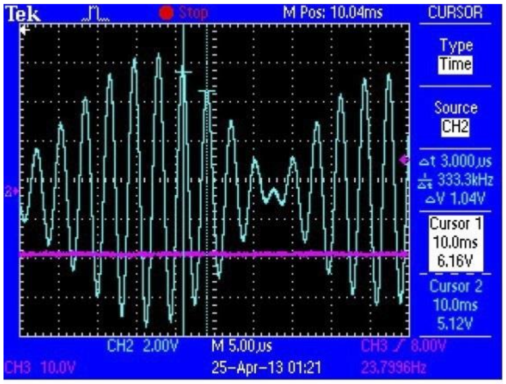


Figure 9 Zoom in sensor's received signal

Review from market off-and-shelf ADCs, there is a very limited selection of simple ADCs with low enough power and high enough resolution under this suggested speed, although modal DBF with sample-and-hold circuitry helps in performing the analogue conversion using a lower speed ADC. The amplifier output is sent into a full-wave rectifier operational amplifier circuit to obtain the magnitude of the negative signals, and then the peak detector circuit is used to detect the maximum magnitude of the output signal over a period of time. The sample-and-hold IC is then controlled at the sampling rate to hold the detected signal. With the sample-and-hold IC, a wider range of lower frequency ADCs can be used in the front-end system. The trade-off of this system is that it assumes the first peak of the received signal contains valid sensing information. In the case of useful data hidden in the remaining ultrasound wave, the useful signal will be lost and not be analyzed by the front-end system. Therefore, the most versatile and costly option is to use a full DBF approach with no risk of data loss in the receiving signals.

As discussed in section 3, the higher the sampling rate of ADC circuitry, more quantitative sensor readings are acquired. In our 333 KHz ultrasonic sensing front-end design, we select ADS805, a 12-bit ADC device running at 20 mega samples per second (Msps) to sample and digitalize the ultrasonic receivers' signals. The selected ADC is from Texas Instruments [12], and has maximum 5V analogue input. This 12-bit ADC has a total of 4096 digital steps, the relationship between analogue sensor value and digital ADC reading is as below equation. Table 1 shows the example readings we read from our designed ultrasonic front-end system using Full DBF collection approach. From the table, the maximum sensor value is 4.75, and minimum detected sensor value is 0.5V. Thus, the designed ultrasonic front-end system is able to sense, amplify, and convert the analogue signals to digital readings. In the final link of the front-end of ultrasound systems, the received pulses are stored digitally for each channel in central control unit (controller); the digital data is then to be further processed in software system using a software ultrasonic image reconstruction algorithm in computer.

$$Ana\log ueSensorValue = \frac{ADCData}{4096} \times 5 \qquad (7)$$

Table 1 Sample of Acquired Analogue Signal via Full DBF approach

Sample #	Digital ADC Data, step	Analogue Value, V
1	2093	2.56
2	2088	2.55
3	2091	2.55
4	1969	2.40
5	2069	2.53
6	2140	2.61
7	1961	2.39
8	2073	2.53
9	2051	2.50
10	2261	2.76
11	2077	2.54
12	2003	2.45
13	1887	2.30
14	2399	2.93
15	2205	2.69

Sample #	**Digital ADC Data, step**	**Analogue Value, V**
16	1501	1.83
17	1809	2.21
18	3890	4.75
19	2415	2.95
20	1693	2.07
21	1881	2.30
22	2489	3.04
23	826	1.01
24	1354	1.65
25	1435	1.75
26	2505	3.06
27	2972	3.63
28	692	0.84
29	1458	1.78
30	2760	3.37
31	2737	3.34
32	421	0.51
33	573	0.70
34	781	0.95
35	3469	4.24
36	1157	1.41
37	957	1.17
38	929	1.13
39	2986	3.65
40	1370	1.67
41	1231	1.50
42	829	1.01
43	2637	3.22
44	2413	2.95
45	557	0.68
46	1321	1.61
47	3495	4.27
48	2513	3.07
49	654	0.80
50	916	1.12

■5.0 CONCLUSIONS

We discussed the trade-offs required in a front-end system designed for ultrasound by first describing the basic operation of such a system, and then indicating what particular performance parameters are required to ensure optimal system operation. The technologies outlined in the sections above have associated strengths and weaknesses regarding their further development towards a system that provides more accurate and real-time measurements. In summary, an industrial ultrasonic flow imaging system is a sophisticated signal processing system. The results from our research studies demonstrate that the various subsystems (a pulser in a multilevel Tx beam former, a fast analogue switch, an operational amplifier with a band-pass filter, and an ADC) in a DBF design are able to provide a comprehensive ultrasonic front-end solution designed with system-level features to provide console-level performance within a small portable form factor or a handheld system.

Acknowledgement

The authors are grateful to the Research Management Centre, Universiti Teknologi Malaysia and for study support from a Research University Grant of Universiti Teknologi Malaysia (Grant No. Q.J130000.2513.02H67, Q.J130000.2513.03H96.).

References

[1] Narouze, S. N. ed. 2011. *Atlas of Ultrasound-Guided Procedures in Interventional Pain Management.* Springer.

[2] Charles Wu and Roger H. Grace. 2013. Thermally-based MEMS Sensors (Part 2) GAS-FLOW: A Critical Technology Comparisonof Various Approaches. Commercial Micro Manufacturing International. 6(4): 44–48.

[3] Samir Teniou and Mahmoud Meribout. 2011. Multiphase Flow Meters Principles and Applications: A Review. *Canadian Journal on Scientific and Industrial Research*. 2(8).

[4] Richard Tweedie. 2012. *Ultrasonic Spectroscopy and the Determination of physical Properties*. Industrial Tomography Systems plc. Application Note.

[5] Mohd Hafiz Fazalul Rahiman, Ruzairi Abdul Rahim, and Nor Muzakkir Nor Ayob. 2010. The Front-End Hardware Design Issue in Ultrasonic Tomography. *IEEE Sensors Journal*. 10(7): 1276–1281.

[6] Eberhard Brunner. 2002. *How Ultrasound System Considerations Influence Front-End Component Choice*. Analog Devices, Inc, Application Note.

[7] Suresh Ram. 2012. *Full Signal path Solution for Portable Ultrasound Systems*. National Semiconductor Corporation, Application Note.

[8] Hudabiyah Arshad Amari, Ruzairi Abdul Rahim, Mohd. Hafiz Fazalul Rahiman, and Jaysuman Pusppanathan. 2011. Front-end Design of an Ultrasonic Tomography Measurement System. *Jurnal Teknologi*. 54 (Sains & Kej.) Keluaran Khas: 289–298.

[9] Maxim. 2010. *Medical Imaging Ultrasound Imaging Systems*. Maxim Application Note.

[10] Thomas Kugelstadt. 2008. *Active Filter Design Techniques*. Texas Instruments Incorporated, Application Note.

[11] Maxim. 2009. *Dual/Quad, Unipolar/Bipolar, High-Voltage Digital Pulsers*. Maxim Datasheet,

[12] Texas Instruments. 2002. *12-Bit, 20MHz Sampling Analog-to-digital Converter*. Maxim Datasheet.