

PVDF Sensor Design and FPGA Implementation of Ultrasound Power Measurement

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Abstract— Ultrasound devices provide either diagnostic or therapeutic purpose in biomedical application. To avoid unwanted power exposure to the patient for safety concern but at the same time maintaining optimum diagnostic and therapeutic effect, ultrasound power meter is used to measure and calibrate the output power and intensity of the ultrasound machine. Most of the current ultrasound power meters are limited for either high power therapeutic or low power diagnostic purposes but not both and it is expensive. To enable Polyvinylidene fluoride (PVDF) for low cost ultrasound power meter, a robust low cost casing has been designed for optimum ultrasound power capturing from both therapeutic and diagnostic ultrasound machine. The system has been designed to minimize interference effect and noise, as well as to stabilize mechanical construction of the sensor. This paper presents a PVDF sensor design of an ultrasound power measurement system that is compact and simple in construction, easy and user friendly, but at the same time provides a reliable power measurement result. The power meter is designed using PVDF sensor and Altera Cyclone II Field Programmable Gate Array (FPGA) technology. Results show that this in-house power measurement system is able to measure 0.5 MHz – 10 MHz of the frequency range and 1 mW/cm² to 10 W/cm² of the intensity range.

I. INTRODUCTION

Ultrasound machines are widely used in many different fields such as industrial and medical technology [1]. There

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are millions of ultrasound medical device spread over the world that is divided into diagnostic and therapeutic that uses the frequency range of 1 MHz to 10 MHz (ultrasound diagnostic) and 0.7 MHz to 3.3 MHz (therapeutic application) with safety emission of 3 W/cm² [2].

For diagnostic purposes, ultrasound is safe, painless for method examining the internal organs that avoids the use of radiation. Sound wave transmitted from ultrasound device is received by the receiver from the echoes bouncing off from soft tissue structures. It can be used to measure the size, to detect structural abnormalities, to determine lump is solid or fluid-filled, or to monitor growth of the fetus during pregnancy. Images with good spatial and temporal resolution are desired using sufficient amplitude of short repetition pulses to obtain an acceptable signal to noise ratio, but avoid biological effects. On the other hand, therapeutic modality using ultrasound that emerged almost five decades ago, has an ability of tissue heating up to some centimeters under the skin [2], [3].

The first objective of inventing power meter is for safety awareness. Besides, it analyzes the relationship between intensity and output power. There are several specifications and standards proposed by the International Electro-technical Commission (IEC) in the beginning of 1960 for measuring the physiotherapy ultrasound machines. It aims to ensure that the output produced by an ultrasound machine is under the safety condition [6], [7].

There are various methods to design an ultrasound power meter such as radiation force method, calorimetric and hydrophone with PVDF sensor. The design presented in [8] has an output power range of 1.5 W to 15 W with resolution of 100 mW/cm², and 0.25 MHz to 10 MHz of the frequency range. The work proposed in [9] has an output range of 0 mW to 300 mW, frequency range of 1 MHz to 10 MHz, but the application is limited to ultrasound diagnostic only. Both designs are based on radiation force method. For the power meters available on the market, lots of them are high cost, less portable and most of them have power resolution between 10 mW/cm² to 100 mW/cm².

PVDF polymer sensors have been used in several applications as a sensing element in pressure sensing, tactile sensor and infrared sensor. The advantages of PVDF are low acoustic impedance that closely matches to the human tissue, water and other organic materials. Besides, PVDF also produces high output voltage and dielectric strength compare with other piezo materials. PVDF is also moist resisting and can be fabricated into unusual designs [10].

On the other hand, Field Programmable Gate Array (FPGA) has emerged as the new technology, which provides

a versatile and cost effective platform in designing systems with shorter design cycle. The FPGA has the ability to be reprogrammed in the field operation. This is useful in measurement system which needs frequent calibration and even to keep on track with standardization, especially regarding ultrasound exosimetry [11]. Nowadays, it is widely accepted that the FPGA is applicable for digital signal processing due to its high speed, reconfigurability, cost-effective and better quality of medical instrumentation. All these advantages make FPGA cross action over the other products available in the market. For instance, the Digital Signal Processing (DSP), has a high sampling rate, but lack of the input-output (I/O) ports. While, microcontroller (μ C) has a low sampling rate and limited I/O ports. Thus, many researches have been carried out to design an ultrasound processing unit using FPGA [13].

This paper presents a PVDF sensor design and FPGA implementation of an ultrasound power measurement system, which consists of signal acquisition unit using PVDF sensor, analog conditional circuit, and digital processing unit design. The complete power measurement system was implemented on Altera Cyclone II DE2 FPGA board to provide a user-friendly and cost effective solution.

II. ULTRASOUND POWER METER SYSTEM ARCHITECTURE

For the hardware implementation, ultrasound power measurement system architecture consists of the signal acquisition unit, analog conditional circuit, digital processing unit and display unit. Fig. 1 shows the overall system diagram.

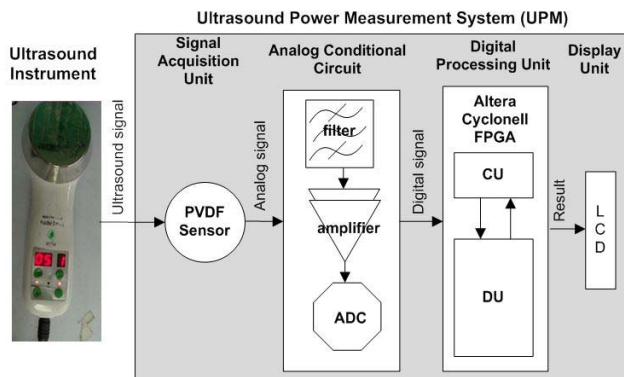


Figure 1. System architecture of ultrasound power meter.

A. Signal Acquisition Unit

The sensor is an in-house design polyvinylidene fluoride (PVDF), which receives the signal from the ultrasound transducer or transmitter (therapeutic probe). PVDF film is a flexible, lightweight material that is available in a variety of thickness and large area. It has the natural capability to convert mechanical energy produced by ultrasound signal into electric energy. Hence, it is useful in detecting ultrasonic field for measurement purposes. It also works in wide frequency range between 0.001 Hz up to 1 GHz, with a low acoustic impedance that closely matches to the human tissues, water and other organic materials. Fig. 2 shows the

transmitter-receiver with specific distance that has been developed.



Figure 2. PVDF transmitter-receiver design.

The SubMiniature version A (SMA) connector illustrated in Fig. 3 is a high frequency component that is used as the base of the PVDF sensor.



Figure 3. PVDF sensor design with SMA connector.

The top section of the SMA connector is connected with brass casing to hold the PVDF films. This sensor is directly connected to the coaxial cable (RG-58). The sensor will be put at the bottom of the PVDF sensor water tank casing depicted in Fig. 4 and totally immersed in the water. To protect the sensor from water leakage, plastic glue was used after it was plugged at the bottom of its casing. The top side of the PVDF sensor must be protected by using epoxy resin hardener. The hardener should not have bubble inside because it can disturb the ultrasound wave and it should be a very thin layer to avoid of being attenuation of the wave. The PVDF sensor water tank casing is designed to protect the sensors from the water leakage that can cause short circuit to the electrical part. The casing is made of the polyvinyl chloride (PVC), with height about 90 mm, diameter of 110 mm, and 2 mm thickness. This type of casing is used because it is light weight, low cost, easy to cut and able to avoid any current leakage to the environment.

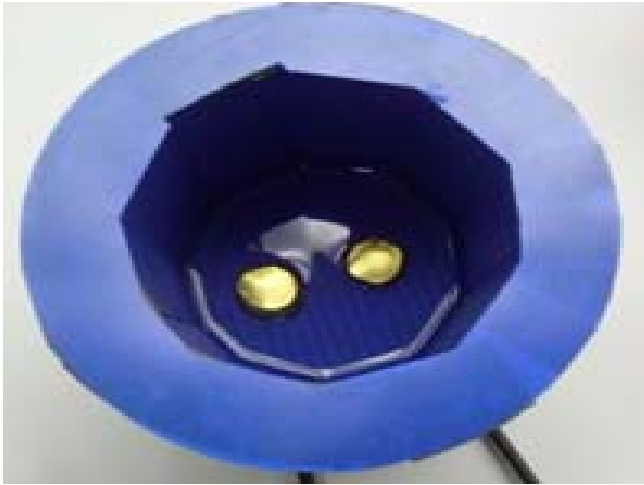


Figure 4. PVDF sensor water tank casing.

The degassed water was used as an ultrasound wave propagation medium due to ultrasound propagation behavior in water is similar with propagation in human tissues. The ultrasonic attenuation in the water was taken as a lower limit on the attenuation that will be encountered in the human body. Most part in the human body consists of low attenuating material such as urine. The use of water prevents measurements in a more highly attenuating material such as liver equivalent gels from representing the highest possible intensities which might be encountered in the body. To prepare degassed water, firstly boil distilled water about 20 minutes and then pour into a suitable container after the water has been cooled. After that, seal container tightly and place it in the refrigerator. The container should be heat resistance glass or thick plastic. Before testing, pour the degassed water into tilted tank test to minimize the turbulence. The surface of test tank water will absorb the oxygen and a change of degassed water is recommended before each experiment.

B. Analog Conditional Circuit

Analog systems have been engaged with the important responsible bordering digital systems in the real world applications such as analog signal processing and conditioning in biomedical measurements. In this paper, the analog conditional circuit is also another in-house design [13], which consists of a filter, amplifier and analog digital converter.

The first interface between the transducer and the analog system is the filter. Analog data are received from actuating unit and filtered to remove noise and disturbance wave from external surrounding or internal circuit that affect the final result. It also rejects the frequency out of interests, which in this case the low frequency is 1 MHz and high frequency cut-off is 10 MHz, respectively, to satisfy medical ultrasound frequencies.

The amplifier circuit is used to amplify the small analog signal to the desired signal range, so that the analog digital converter (ADC) could convert the signal easily. Electrical impedance of the components should also provide also close

match with the corresponding sensors. To match for interfacing with ADC in further data acquisition stage, output resistor, capacitor and voltage were prepared to create a better signal for measurement.

The ADC is used to transform the PVDF sensor analog output signal to a digital signal which is later sent to the FPGA for power measurement computation. Resolution of the converter indicates the number of discrete values it can produce over the range of analog values. The value represented in this system is 0 to 1023 issued for 10 bits resolution and 0 to 4095 for 12 bits resolution. Each resolution level is expressed in unit of volt.

C. Digital Processing Unit Design

A digital processing unit designed in Altera Cyclone II FPGA board is done with digital processing and data management works.

Temporal-average intensity, I_{TA} (mW/cm^2) is the algorithm of average ultrasound intensity calculated over the time between pulses involves in FPGA. Input signals from sensors would be converted to digital form by ADC and then buffered into memories. Then, the voltage value obtained to perform the ultrasound intensity based on (1). PIC is used for the LCD to display the computation result

$$I_{TA} = \frac{I}{N} \sum_{i=0}^N \frac{V(i,x)^2}{M(f)^2 \cdot \rho \cdot c} \quad (1)$$

where N is number of sampling, $V(i,x)^2$ is sensor's output voltage dependant on temperature and distance, $M(f)^2$ is sensitivity of sensor, ρ is density of medium, and c is speed of sound in the medium. Arithmetic operations in a linear equation such as addition, multiplication, division and power are involved. All denominators are constant values in this system as shown in Table I.

TABLE I. THE CONSTANT VALUE OF EACH DENOMINATOR SYMBOL

Symbol	Value
Sensitivity of sensor, $M(f)$	$1e^{-7}$ V/Pa
Density of medium, ρ	1000 kg/m^3
Speed of sound, c	1480 m/s
Sampling rate, N	500

Fig. 5 shows the digital processing unit architecture consists of a control unit (CU) and data path unit (DU). The DU consists of two memory modules (MEM1 and MEM2) to buffer the input data after the ADC conversion, arithmetic-logic-unit (ALU), accumulator (ACC), concatenator, and multiplexer (MUX) to execute (1) which is controlled by a master controller CU.

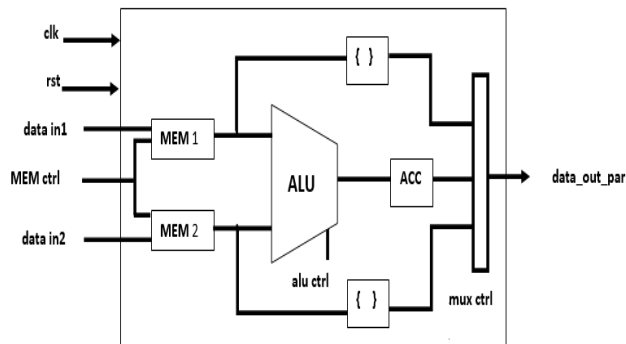


Figure 5. RTL block diagram of ultrasound processing unit.

The complete digital processing unit is then downloaded into Altera Cyclone II DE2 board with a proper pin assignment, so that it can receive data from analog conditional circuits and display the result on LCD, respectively. The PIC used as the driver for LCD need a specific graphical data to be programmed. Without these data, PIC is unable to be processed and displayed with the corresponding text. The graphic data will convert the information and light up the LCD according to the coordinate. This complete digital processing unit is designed using Verilog at Register Transfer Level (RTL). Altera Quartus II EDA software is used as the text editor, synthesis tool and timing analysis, whereas the Mentor Graphic ModelSim student edition is used as a simulator to verify the sub-system functionality.

III. SIMULATION AND DISCUSSIONS

The Ultrasound processing system able to measure the frequency range between 0.5 MHz – 10 MHz and the intensity range between 1 mW/cm² to 10 W/cm² was prepared based on characterization experiment verification [13]. To observe the effect of frequency changes, function generator was supplying sinusoidal signal with 1 V_{peak} and frequency between 10 kHz and 10 MHz to the transmitter film. Based on previous experiments [13] the voltage was varied between 120 mV_{peak} and 1 V_{peak} while keeping the frequency at 1 MHz. Table II summarizes the overall system performance and design specification of the proposed ultrasound power meter.

TABLE II. PROPOSED ULTRASOUND POWER METER SYSTEM PERFORMANCE AND SPECIFICATIONS

Input ports	12-bit PVDF sensor signal
Output ports	LCD
Frequency range	0.5 MHz – 10 MHz
Intensity range	1 mW/cm ² to 10 W/cm ²

Fig. 6 shows the ultrasound power measurement system hardware prototyping on Altera Cyclone II DE2 board. The ultrasound instrument used for system functionality verification is the Commercial Ultrasound Therapy Portable GB-818 (Green Ultrasonic Science & Technology Equipment

Manufacturing). It has 1 MHz of frequency and 8 intensity levels with both continuous and pulse modes. The ultrasound probe area is 5 cm².

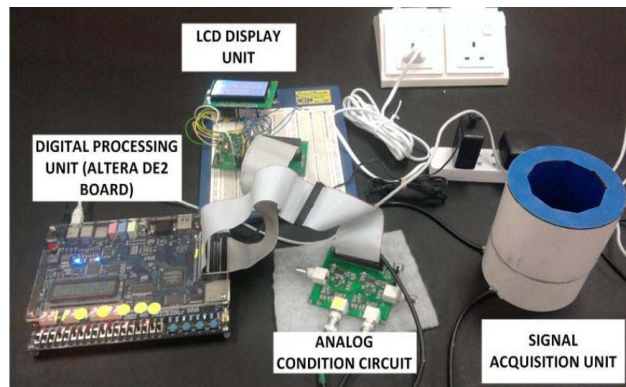


Figure 6. Hardware prototyping of ultrasound power meter.

The FPGA clock should be able to capture at maximum 10 MHz full form of ultrasound signal. Therefore, FPGA clock must reach the maximum frequency at 21.32 MHz in order to make good sampling of ultrasound signal. 5 V_{peak} are chosen for voltage work level. Storage capability is also considered to catch full cycle of ultrasound waveform.

Fig. 7 shows the functional simulation of the top level module from ModelSim.

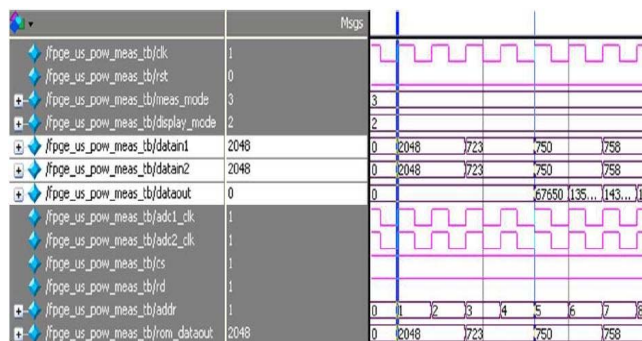


Figure 7. The simulation for overall system.

Input of ultrasound signal from two sensors are illustrated by *datain1* and *datain2*. The *rom_dataout* produced by the internal module inside the test bench in which digitized ultrasound signal from data converter simulation. From the simulation, *dataout* shows after 80 ns. The result identifies the ultrasound power meter is functionally correct according in the (1). The comparisons in this paper with existing products are described in Table III.

TABLE III. COMPARISON OF THIS PAPER WITH OTHER PRODUCT

Product / Features	Ultrasound Power Meter UPM-DT-100AV. (Ohmic Instrument Co.)	Ultrasound Watt Meter UPM 2000 (Nitech Biomedical & Industrial Test Instruments)	Ultrasound Power Meter – UPM – 30 (Ohm Instrument Co.)	Proposed Work
Measurement range	0 W to 30 W	0.1 W to 30 W	0 W to 30 W	1 W/cm ² to 50 W/cm ²
Frequency range	0.5 MHz to 10 MHz	0.5 MHz to 10 MHz	0.5 MHz to 10 MHz	0.5 MHz to 10 MHz
Ultrasound test media	Degassed water	Degassed water	Degassed water	Normal water or ultrasound gel
Resolution	200mW	0.1 W	150m W	0.003 mW/cm ²
Power source	12 VAC,500 mA power adapter	9 V	-	15V
Sensor	-	-	-	PVDF
Ultrasound Applications	-	-	-	Diagnostic and therapeutics
Display	3-Digit LCD	LCD	-	LCD
Communication Interface	RS-232	RS-232	RS-232	USB

IV. CONCLUSION

This paper has presented an in-house ultrasound power measurement system with a low cost, user friendly and high precision capability suitable for medical application. The unique design has been obtained while the test results show a possibility to use it for an ultrasound intensity measurement purpose.

Due to its effects for fast system prototyping, the manufacturer can expect to supply architecture design updates from time to time. It is very beneficial for measurement system which requires frequent calibration and for standardization especially regarding ultrasound exposimetry. However, the current power meter has power resolution limitation, no possibility for further data analysis. The future work will aim to solve all these aforementioned issues.

In future for further modification towards an ultrasound, digital processing unit is desired to improve the overall system performance. Hence support the real time analysis and optimizing hardware area (e.g. reducing logic element).

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