UNIVERSITI PUTRA MALAYSIA

STIMULUS SIGNAL GENERATION FOR FIELD PROGRAMMABLE GATE ARRAY- BASED GAMMA SPECTROSCOPY SYSTEM

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By

NUR AIRA BINTI ABD RAHMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

February 2016

DEDICATIONS

Dedicated to my beloved husband & sons

Mohd Izwan, Muhammad Darwisy & Imran Hakim

for their endless support.

My Mother,

Aiishah Md Shah

My late Father

Allahyarham Abdul Rahman Md Derus

And My Siblings

Nur Mardhiah, Muhammad Abd Illah, Abd Qadir, and Abd Barr

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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February 2016

Chairman : Associate Professor Abdul Rahman Ramli, PhD
Institute : Advance Technology

Code simulation or test bench enables verification of new Field Programmable Gate Array (FPGA) design to be done during code development stage. However, the conventional method to obtain stimulus data for simulation of FPGA based multichannel analyzer (MCA) requires actual radiation detector with tedious setup and dedicated software to acquire and store the acquired data. In addition, the signal parameters cannot be manipulated once data are acquired. The first objective of this thesis is to develop a tool that can systematically generate stimulus data required for code simulation of new FPGA based MCA. The second objective is to design the architecture of MCA on FPGA, the test benches required to verify the MCA functionality, and to simulate the MCA by utilizing input stimulus generated on the first objective.

PulseGEN is the developed software that can generates Analog to Digital Converter (ADC) sampling data of the detector amplifier signal in gamma spectroscopy system. PulseGEN operations are divided into two modes; Single/Pile-Up mode and Continuous Random mode. In Single/Pile-Up mode, ADC data for one pulse or two pile-up pulses are generated. These data will be used to verify MCA pulse height measurements and pile-up rejection. In Continuous Random mode, PulseGEN generates continuous ADC data to simulate actual nuclear counting process. These data will be used to verify the histogram/spectrum produced by MCA and to evaluate the overall performance of the MCA.

To demonstrate the application of PulseGEN data, an FPGA based MCA is designed. The top module *MCA_Controller* consists of pulse height analyzer (PHA), dual port RAM (DPRAM), and counter. PHA is designed as a finite state machine (FSM) whereas the DPRAM is configured to have 4096 64-bit words memory. The design is successfully synthesized by using Xilinx

Synthesis Technology (XST) Software. Two test benches were created to simulate *MCA_Controller* code. TB_MCA_FSM will verify the PHA pulse measurement results and TB_MCA will evaluate the spectrum generated as well as the overall functionality of the MCA.

PulseGEN simulation data have been compared against actual Sodium Iodide (NaI) detector and pulser output pulses in terms of pulse height, width, and shape. Difference on pulse heights is found less than 1% while the difference on pulse width is less than 3%. Pulse shapes of the NaI detector, pulser, and PulseGEN are also comparable to each other. By using PulseGEN data as stimulus, code simulation results from the test bench are presented. The functionality of the MCA design is verified as the simulation results agreed with the actual measurement values.

In conclusion, PulseGEN has successfully generates stimulus data required for code simulation of new FPGA based MCA. The architecture of MCA on FPGA has been designed, and the test benches results confirmed that the MCA is working according to specification. The contribution of this thesis is PulseGEN that is able to generate various types of nuclear pulse ADC data. PulseGEN data enable systematic simulation of the MCA code. The simulation results will assist designer to optimize the output of the designed MCA for the target application.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

PENGHASILAN ISYARAT RANGSANGAN UNTUK SISTEM SPEKTROSKOPI GAMMA BERASASKAN FIELD PROGRAMMABLE GATE ARRAY

Oleh

NUR AIRA BINTI ABD RAHMAN

Februarl 2016

Pengerusi : Profesor Madya Abdul Rahman Ramli, PhD
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Ujian simulasi kod atau dikenali juga sebagai *test bench* merupakan ujian yang membolehkan pengesahan sesebuah reka bentuk *Field Programmable Gate Array* (FPGA) yang baru dilakukan seiring dengan pembangunan kod tersebut. Walaubagaimanapun, kaedah konvensional untuk mendapatkan data rangsangan bagi menjalankan simulasi *multichannel analyzer* (MCA) berasaskan FPGA memerlukan pengesan radiasi yang sebenar dengan melalui langkah penyediaan yang rumit serta perisian khusus untuk memperoleh dan menyimpan data tersebut. Di samping itu, parameter isyarat tidak boleh dimanipulasi setelah data diperolehi. Objektif pertama tesis ini adalah untuk membangunkan perisian yang boleh menjana data rangsangan yang diperlukan bagi menjalankan simulasi kod MCA berasaskan FPGA secara sistematik. Objektif kedua tesis ini adalah untuk mereka bentuk MCA berasaskan FPGA, membangunkan *test bench* yang diperlukan untuk menentu sahkan fungsi MCA tersebut, serta menjalankan ujian simulasi kod MCA dengan menggunakan data rangsangan yang dijana pada objektif pertama .

PulseGEN adalah perisian yang telah dibangunkan yang boleh menjana data persampelan *Analog to Digital Converter* (ADC) bagi isyarat penguat pengesan radiasi dalam sistem spektroskopi gamma. Operasi PulseGEN terbahagi kepada dua mod; mod *Single/Pile-Up* dan mod *Continuous Random*. Pada mod *Single/Pile-Up*, data ADC yang dihasilkan mengandungi satu isyarat denyut atau dua isyarat denyut yang bertindih. Data ini akan digunakan untuk mengesahkan pengukuran amplitud isyarat denyut dan penolakan isyarat denyut yang tertindih. Pada mod *Continuous Random*, PulseGEN mensimulasi data ADC semasa proses pembilangan (*counting process*) berlaku. Data ini akan digunakan untuk mengesahkan histogram/spektrum yang dihasilkan oleh MCA serta menilai fungsi MCA secara menyeluruh.

Sebuah MCA berasaskan FPGA dibangunkan bagi tujuan mendemonstrasi penggunaan data PulseGEN. Modul utama *MCA_Controller* terdiri daripada *pulse height analyzer* (PHA), *dual port RAM* (DPRAM), and pembilang isyarat denyut. PHA direka bentuk sebagai sebuah *finite state machine* (FSM) manakala konfigurasi DPRAM mengandungi 4096 64-bit memori. Reka bentuk ini telah berjaya disintesis dengan menggunakan perisian *Xilinx Synthesis Technology* (XST). Dua unit *test bench* dibangunkan bagi menjalankan ujian simulasi kod *MCA_Controller.* TB_MCA_FSM akan digunakan bagi tujuan pengesahan keputusan pengukuran amplitud denyut oleh PHA, sementara TB_MCA akan digunakan untuk menilai spektrum yang dihasilkan oleh MCA.

Perbandingan di antara data simulasi PulseGEN dan data daripada pengesan radiasi *Sodium Iodide* (NaI) dan *pulser* dari aspek amplitud, kelebaran isyarat denyut, serta bentuk isyarat denyut telah dijalankan. Hasil perbandingan mendapati perbezaan pada amplitud isyarat adalah kurang dari 1% manakala perbezaan pada kelebaran isyarat adalah kurang daripada 3%. Bentuk isyarat bagi pengesan radiasi NaI, *pulser*, dan PulseGEN didapati hampir menyerupai di antara satu sama lain. Dengan menggunakan data PulseGEN sebagai rangsangan, keputusan kod simulasi dari *test bench* telah ditunjukkan. *Test bench* mengesahkan bahawa MCA menghasilkan keputusan pengukuran yang sama dengan nilai pengukuran yang sebenar.

Sebagai kesimpulan, PulseGEN telah berjaya menghasilkan data rangsangan yang diperlukan bagi ujian simulasi kod MCA berasaskan FPGA. Keputusan *test bench* membuktikan bahawa MCA yang dibangunkan berfungsi mengikut spesifikasi yang telah ditentukan. Sumbangan utama kajian ini ialah PulseGEN yang mampu menjana pelbagai bentuk isyarat denyut pengesan radiasi serta membolehkan simulasi kod MCA dijalankan secara sistematik. Keputusan simulasi ini akan membantu pereka untuk mengoptimumkan output MCA mengikut kesesuaian aplikasi sistem yang dibangunkan.

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I certify that a Thesis Examination Committee has met on 11 February 2016 to conduct the final examination of Nur Aira binti Abd Rahman on her thesis entitled "Stimulus Signal Generation for Field Programmable Gate Array-Based Gamma Spectroscopy System" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
ALARA	As Low As Reasonably Achievable
ASIC	Application Specific Integrated Circuit
CPS	Count Per Second
DPRAM	Dual Port Random Access Memory
FPGA	Field Programmable Gate Array
FSM	Finite State Machine
GUI	Graphical User Interface
LlTh	Lower Level Threshold
MCA	Multichannel Analyzer
NaI Detector	Sodium Iodide Detector
NIM	Nuclear Instrumentation Module
PHA	Pulse Height Analyzer
RAM	Random Access Memory
RTL	Register Transfer Level
SRAM	Static Random Access Memory
S-G shaper	Semi Gaussian shaper
T_P	Pulse peaking time
T_F	Pulse fall time
T_W	Pulse width
UlTh	Upper Level Threshold
UUT	Unit Under Test
VI	Virtual Instruments (Labview)
XST	Xilinx Synthesis Technology

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Nuclear science and technology goes beyond nuclear power and nuclear weapon. In everyday life, nuclear technology could be seen in agricultural developments, health diagnostic and treatments, industrial applications, and many more. Nuclear instruments are the fundamental tools for deriving benefits in these applications. While the applications might vary, functions of these instruments typically revolve around radiation detection, radiation measurement, signal processing, data acquisition, and data interpretation [1]. Multi-channel analyzer (MCA) is a significant instrument for various nuclear applications. It performs radiation measurements and produces radiation energy spectrums. Based on the energy spectrums, important information such as radionuclides identity and intensities could be quantified and qualified.

Nowadays, most modern instruments are driven by digital processor. Among the highlighted advantages of digital processors are high speed, low power, compact size, low cost, re-programmability, and low probability of fault due to reducing number of components. Digital processors such as Application Specific Integrated Circuit (ASIC), Field Programmable Gate Array (FPGA), and microcontrollers have emerged as key components in the design of nuclear instruments. Flexibility and abundance of hardware resources available inside these chips allows customized design and possibility to implement the entire system on one chip [2-7].

Regardless of the digital processor types or manufacturers, code simulation or test bench is an essential stage in the design flow of digital processors. Test bench enables functional and timing verification of the new design to be done during code development stage. Hence most of the design errors can be detected and corrected prior to hardware prototype fabrication [8-10]. A successful test bench requires adequate input conditions called stimulus. During simulation, stimulus will be applied as input to the code while the output will be observed and analyzed according to the desired results.

1.2 Overview of Gamma Spectroscopy System

Gamma spectroscopy system consists of five main components; radiation detector, high voltage supply, pre-amplifier, amplifier, and multichannel analyzer. Block diagram and connection between each component is shown in Figure 1.1. The front end of the system is radiation detector that converts gamma ray to voltage pulse. Output of radiation detector is electrical charge proportional to the amount of gamma-ray energy absorbed by the detector. The pre-amplifier is the first stage amplification of detector output pulse. It provides proper interface between the detector and the amplifier by providing high impedance load for the detector and low impedance source for the amplifier [11].

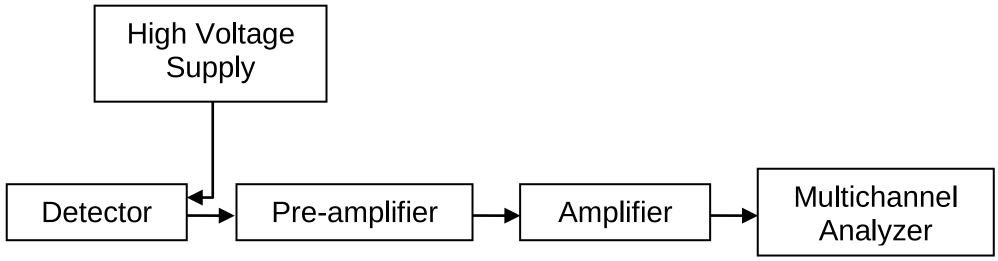

Figure 1.1: Block diagram of gamma spectroscopy system

Output of the pre-amplifier consists of a step function followed by slow exponential decay, which is not suitable for direct measurement of peak height. Hence amplifier serves to shape and further amplifies the pulse to its optimized shape and height while providing pole-zero cancellation, baseline restoration, and pile-up rejection [11-13]. In order to yield optimum signal to noise characteristics and count rate performance, amplifier output is shaped to a near-Gaussian shaped pulse [11]. Finally multichannel analyzer performs pulse height measurements and records the events in its memory to build a histogram. This histogram or pulse height spectrum maps the distribution of pulses with respect to pulse height that corresponds to the energy spectrums observed by the particular detector. Based on the energy spectrums, important information such as the radionuclide identity and its radiation intensity can be quantified and qualified [11, 14].

1.3 Problem Statement and Motivation

As opposed to analog system, digital processors such as FPGA provide less "test or inspection points". This is due to digital nature, where the information is in digital form and contained within the ICs [1]. Therefore, FPGA simulation is an important stage in the design cycle. It enables designer to detect and correct design errors during coding or programming stage. These coding errors are typically harder to fix if they are discovered in later stage such as hardware prototyping stage.

However, in FPGA based nuclear spectroscopy design, testing is typically done in hardware prototyping stage by using actual input signal. The input signal is produced by hardware instruments that involve detector, signal processing circuit, amplifier, and analog to digital converter (ADC). Acquiring and recording the physical signal as input for design simulation will requires tedious instrument set-up and consume large memory space [10]. In addition, the signal parameters cannot be manipulated once the data is acquired. Hence the common practice is to skip software and code simulation stage and perform the design testing by using actual hardware.

The aim of this research is to develop a software tool that can generate the required data to run code simulation of FPGA based MCA. The output of this research will enable MCA code simulation by providing the required input stimulus without the need of actual hardware. Apart from error detection and correction, simulation will enable designer to study the effect of varying certain design parameters and choose the best configuration that will optimize the MCA result and output.

1.4 Thesis Objectives

This research is divided into two objectives:

1. To develop a tool that can systematically generate stimulus data required for code simulation of new FPGA based MCA for gamma spectroscopy system.
2. To design the architecture of MCA for gamma spectroscopy on FPGA and the test benches required to verify its functionality by utilizing input stimulus generated in (1).

1.5 Thesis Organization

This thesis has been structured into six chapters. Chapter 1 provides general background and overview of the research. It highlights the problem statement and objectives of the research. Chapter 2 presents a review of literature related to FPGA-based gamma spectroscopy system and FPGA code simulation for functional verification. Chapter 3 describes the steps and procedures for the design and simulation of the FPGA based MCA. Chapter 4 describes the design of software based nuclear pulse generator or PulseGEN. The results and discussion is presented in Chapter 5. Finally Chapter 6 concludes the thesis and provides recommendation for future work.

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