FPGA-based System for Velocity of Detonation Measurements on Detonating Cords

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***Abstract*—This work presents the most important aspects of the development of a system designed to measure velocity of detonation (VOD) of detonating cords used in the mining industry. The system utilizes the point-to-point measuring method, employing optical fibers as sensing elements. It comprises an FPGA device that enables a multi-channel, easily scalable system, and a microcontroller that manages the user's interface. This instrument was developed in response to a request from a detonating cords manufacturing company, addressing the absence of such equipment in the national market.**

Keywords— velocity of detonation, detonating cord, FPGA

I. Introduction

Velocity of detonation (VOD) refers to the speed at which the detonation wavefront propagates through an explosive charge [1]. Different types of explosives have different VOD and the increase in VOD value is related to the explosive's power. Thus, accurate measurement of VOD is critical in the industrial explosives field as it characterizes its quality and performance [2], [3].

In the mining industry, detonating cords are flexible tubes containing explosive material inside, characterized by their high VOD with values above 5,000 m/s, currently reaching values close to 8,000 m/s [4-6]. They are used primarily to initiate detonators and as a main line to connect blastholes [7].

VOD measurement in various industries, including mining, oil, and charge/accessory manufacturing, employs a range of instruments and methods [8-10].

In general terms a system for measuring VOD requires sensor elements that are in contact with the explosive and a recorder to store the changes over time, to finally visualize the VOD on a display. Measurement systems based on continuous methods use wires or probes arranged along the explosive to measure and record the variation of an electrical variable over time. In discontinuous methods, measurements are made at specific points in the explosive charge (point-to-point), using, for example, fiber-optic cables as sensing elements arranged at different points in the explosive. The VOD is obtained by measuring the time it takes for the shock wave to travel from one sensor to other and knowing the separation distance between them [3], [11].

There are several commercial options for VOD measurement worldwide, which have been used in different studies on measurement methods and properties of explosives [7], [10], [12]. However, the alternative of low-cost devices has been little explored, particularly in developing countries, and specifically VOD meters based on Field Programmable Gate Array (FPGA) devices. In this context, the works presented in [13-15] are deemed to be of relevance.

A novel system for VOD measurements utilizing FPGA technology was presented in [13]. It is a high-speed digital data recorder designed for measuring VOD in field applications. In [14], a VOD measurement system using two optical fibers as sensors was proposed. The system employs an FPGA to process the signals, which enhances the measurement accuracy and simplifies the system debugging. The device displays the obtained VOD on a display. The development and testing of a VOD meter called OPTIMEX, which uses multiple independent fiber optic probes as sensors, was presented in [15]. The system is comprised of an FPGA (digital system) and a microcontroller that manages the interface with the user.

This paper presents the development of a low-cost FPGA-based system to measure VOD at the specific request of a detonating cords manufacturer with ISO 9001:2015 certification. This is in view of the absence of this type of device at the national level and in much of Latin America. The critical and challenging point is related to the processing speed required to measure up to 10,000 m/s, with a time measurement resolution of 0.1 µs. This led to the decision to use an FPGA, which allows for the implementation of a multi-channel (5 in this case) and easily scalable system. Thus, the developed system covers most applications in the mining and oil industry.

The paper is organized as follows. Section II describes the measuring method and the functional aspects of the implemented VOD. Section III discusses the results obtained, and finally, the conclusions of the work are presented.

II. System Description

A. Measuring Method

The developed system uses fiber-optic cables as sensing elements to detect and transmit the light signal generated by the detonation wavefront. It is a "point-to-point" method, where the first fiber-optic cable signals the start of the time count and the last fiber, fixed at a known distance on the detonating cord, stops it. The distance between measurement points (called segments), divided by the time difference between the signals transmitted by the optical fibers, provides an accurate estimation of the VOD value. Using the same principle, five measurement points were implemented enabling the acquisition of four VOD measurements, which should exhibit comparable values. Otherwise, this would indicate the presence of a defect or a quality issue with the detonating cord.

The times to be measured range from 1 µs to 1,000 µs with a resolution of 0.1 µs. The passage of the wavefront through a point on the sample (detonating cord) is detected by means of a plastic optical fiber inserted perpendicularly on the cord, as illustrated in Fig. 1, and connected to the VOD meter. The equipment is capable of measuring up to four travel times (five points) and calculating their velocities. The results are displayed on an LCD display, including the measured times, entered distances and calculated VODs. In addition, the system allows up to three tests to be stored with their respective date and time (to be entered for each of them). A diagram of the implemented measuring system is shown in Fig. 2.

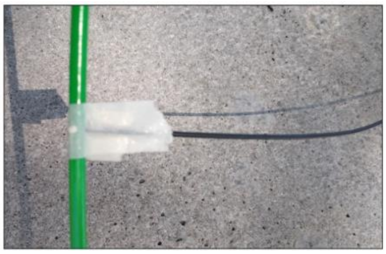

Fig. 1. Optical fiber inserted on the detonating cord.

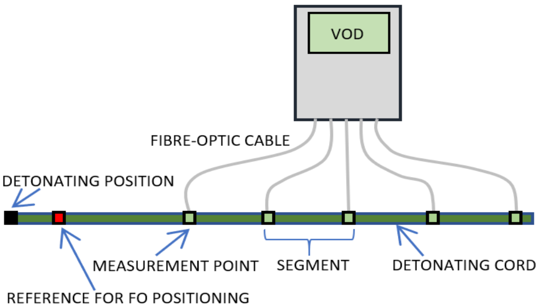

Fig. 2. Measuring method diagram.

B. *Functional Description*

Fig. 3 shows the block diagram of the VOD meter, which comprises a pulse shaper (PS) connected to the fiber-optic cables (FO), a digital system (DS), a host, a keyboard, and a display. The DS block allows to determine the time elapsed between the transition of the S0 signal (taken as the start of the count) and the transitions of the digital signals S1 to S4. This is achieved through the use of a pulse counter produced by a 50 MHz oscillator, which allows a resolution of 20 ns.

The PS block converts the light signals from the FO inputs into digital electrical signals (S0 to S4) via analogue output optocouplers for polymer optical fiber applications and high-speed response comparators. A low-to-high transition at the comparator output indicates the passage of the detonation wavefront at the respective measurement point.

Signals S0 to S4 enter a state machine (SM) which is responsible for the DS control. For the functioning of the SM, 40 states were defined. For the sake of simplicity, its operation will be briefly discussed. When the SM is enabled for testing (armed state), a rising edge of S0 in the SM triggers the synchronous 16-bit counter via CTENA signal, starting the count. The SM enables the registers (REG0-REG3) that store the number of counted pulses at transitions of signals S1 to S4. On the one hand, if no rising edge occurs at the Sx inputs of the SM, the counter will reach the end value of the count. On the other hand, if all the rising edges are detected, the counter will also reach the end value of the count and will bring the SM to the end of measurement state through the CTEND signal. In this state, the counter is disabled through the CTENA output of the SM, stopping the count to go to the register selection state. From this instance, the SD starts the process of sending to the HOST the data stored in the registers, sequentially selecting (SEL output of the SM) each register output (inputs to the 8-1 MUX) to enter the data into the UART.

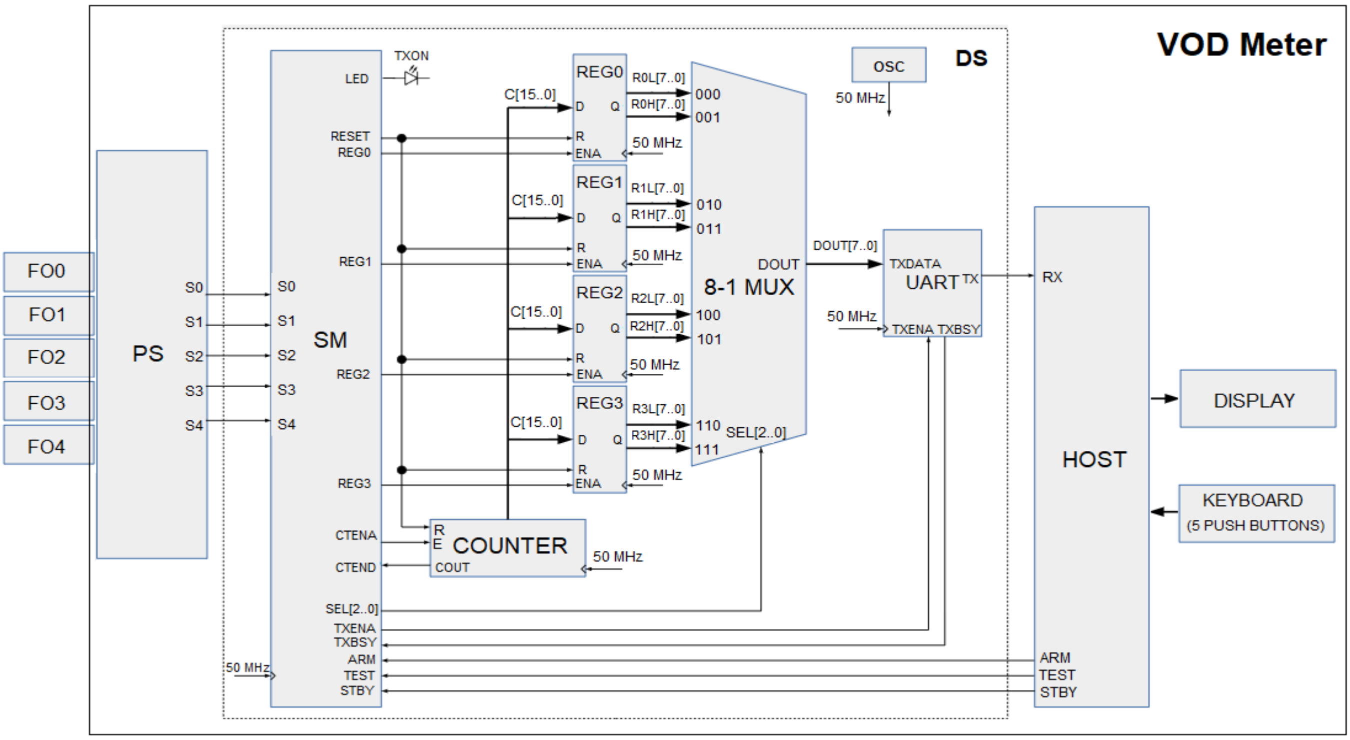

Fig. 3. Block Diagram of the VOD meter.

Once the transmission is finished, the SM enters in the standby state until a new arming order is received. Once the data is received in the host, it calculates the partial times: t0 = tREG0, t1 = tREG1 - tREG0, t2 = tREG2 - tREG1 and t3 = tREG3 - tREG2. If the calculated times are less than 0, they are assigned the value 0.0. If the distances are 0 (no value other than the default was entered), the times are assigned the value 0.0. The times are then converted to ASCII code, preparing the information to be sent to the display. If the times are 0.0, "---" is displayed, and if the times are greater than 999.9, "OVL" is displayed. Then the velocities in m/s are calculated. To determine the four VODs, the host calculates the time of each segment (number of counted pulses x period of the pulses) and then the velocity of each segment (using the distance data entered by the operator). The velocities are then converted to ASCII, preparing the information to be sent to the display. If the velocities are 0.0, "---" is displayed, and if the velocities are greater than 9999.0, "OVL" is displayed. Finally, the data is shown on the display.

The SD was implemented on an FPGA device and the host on a microcontroller. This alternative was chosen based on the user's requirements regarding possible future modifications to the user's interface. For this reason, the microcontroller-based host alternative was implemented due to the ease and versatility of the software modifications.

The DS was implemented using an FPGA device from Altera's Cyclone II family supported on a generic EP2C5T144 miniboard. VHDL language was used for the hardware description. For both the description and the configuration of the DS hardware, the Quartus® II Version 13.0.0 Web Edition tool was used. The UART module was implemented by means of public HDL description.

The HOST was implemented using a Texas Instruments MSP430F247 microcontroller. It uses the flash memory available to the user to store the tests. A human-machine interface was established through a 4x20-character display and a keyboard comprising five push buttons with specific functions. Code Composer Studio™ was chosen as software development environment.

The VOD meter has five push buttons, four of which have dual functions. The functions are as follows: ENTER to start the test, UP/ARM to move up or arm, DOWN/STORE to move down or store, LEFT/NEW to move left or run a new test, and RIGHT/MENU to move right or return to the menu screen. The function of each push button is determined by the screen it is on.

III. Results

Functional simulation results using ModelSim® software are illustrated in Fig. 4. The input signals to the SM are shown: ARM at logic value '1', TESTIN at logic value '0' and STBY at logic value '0'. On a rising edge at S0, the pulse counting starts and the value is displayed at the output of the registers.

Fig. 5 shows a view of the developed VOD meter and Fig. 6 shows the VOD values obtained in a field test and presented on the display. Table I summarizes the main specifications of the developed equipment.

Regarding resources, 207 out of 4,608 FPGA logic elements (4%), 151 out of 4,608 dedicated logic registers (4%) and 14 out of 89 pins (16%) were used, showing that the system can be scaled without changing the FPGA.

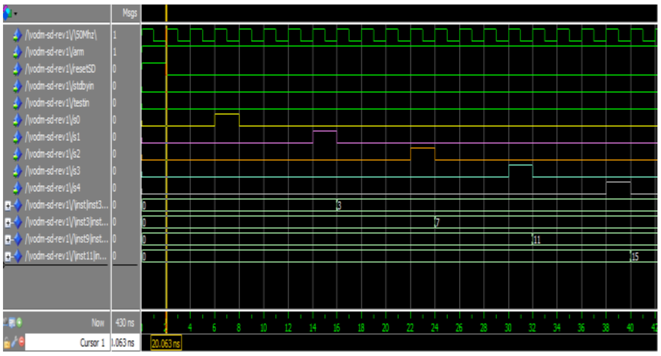

Fig. 4. Functional simulation.

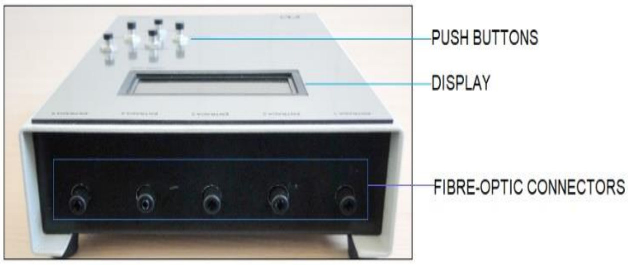

Fig. 5. VOD meter.

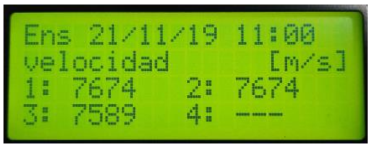

Fig. 6. Values on the VOD meter display.

TABLE I. VOD Meter Main Specifications

Characteristics	
Parameter	**Specification/Value**
Input channels	5 inputs for fiber-optic connection
Maximum measurable time	999,9 µs
Time resolution	100 ns ± 20 ns
Maximum measurable distance	The sum of distances cannot exceed 999 cm
Maximum measurable VOD	9999 m/s
Memory	Storage capacity of 3 tests

IV. Conclusion

A low-cost FPGA-based VOD meter was developed, enabling measurements on detonating cords with VOD values of up to 8,000 m/s. The hardware design allows for scalability to accommodate more channels by reusing the hardware description made.

The VOD meter has been transferred and is currently being used for field measurements at the detonating cord manufacturer.

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