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Digital Ultrasonic System for Internal Corrosion Assessment on Oil Pipelines

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Abstract. *This work describes a digital ultrasonic system designed to be used on inspection pigs for assessing the level of corrosion on the internal wall of oil pipelines. Ultrasonic echoes are used to measure the distance from ultrasonic transducers to the surface of the wall. Beyond this conventional technique, the system measures the wall thickness, processing the echoes that are generated by multiple reflections of the acoustic wave inside the metallic wall. The signals are digitally acquired by fast A/D converters and processed in real-time by application-specific hardware implemented in a Field Programmable Gate Array, a high capacity programmable device. Local peaks of the signal are used to estimate the time of arrival (TOA) of the multiple echoes. The first TOA - the one of the echo from the first wall interface, is estimated by the instant of the global maximum of the acquired signal. The second TOA – from the second wall interface, is associated to the local maximum of the signal inside a time window that is triggered after the detection of the first TOA. A piece of a pipeline was scanned in a water tank and the results of these experiments are presented. The system was able to correctly estimate the first TOA instants even under poor noise-to-signal conditions. Estimation of the second TOA degrades when scanning severely corroded regions, nevertheless the system was capable to determine the average thickness of the wall even in these situations.*

Keywords: *ultrasonic pig, ultrasonic non-destructive testing, real-time DSP*

1. Introduction

Pipelines are tubular structures, used to transport petroleum and other fluids, and are important structures for the Oil and Gas Industry, since most of the oil and gas production is distributed via pipelines. This distribution requires high levels of safety and trust, because pipeline failures can originate large accidents. Major accidents related to pipeline leakage have occurred in recent years with terrible consequences, ranging from environment damages to human fatalities (Papadakis, 1999). People tolerance to this kind of accident is very low nowadays, and the image of the oil companies is compromised if they do not take measures to avoid these problems.

The lifetime of an oil pipeline is approximately 20 years, and it has been estimated that near 40% of the world-wide pipelines have reached this time (Azevedo, 2007). The main deterioration reason is that the ducts are generally exposed to corrosive elements (such as salty water and sand), and even the transported fluids can cause corrosion. Efforts have been made to extend residual life of the pipes, aiming to reduce costs of their total replacement. Therefore, it is very important to constantly inspect these ducts, looking for cracks and corrosion pits, which eventually can cause leakages.

Since the diameters of the ducts are relatively small (200 mm to 500 mm), and pipelines can have kilometers of length, an *in-situ* inspection is not possible. To solve this problem, the oil industry uses special equipment that can be inserted in the ducts, known as *pigs*.

Pigs are equipments that carry others instruments and sensors through the interior of pipelines, to collect different types of data that are be analyzed to give the real conditions of the duct. Examples of types of sensors that are used are magnetic, contact and ultrasonic. Pigs are used for more than 40 years, and from generation to generation new technologies are developed to improve the results or to follow new inspection regulations (Park et. al., 2002).

Among these methods, ultrasonic inspection has provided good results in recent years (Furukawa et. al., 1999). Advances in improving the detection of the signal are presented by Reber (2002). His work mentions the use of FPGAs on the signal processing, with a digital approach to determine the moment of arrival from an ultrasonic echo. Another example is the work of Suh et. al. (1999) that describes a DSP technique for detecting cracks in bolts with ultrasound.

Ultrasonic inspection using DSP techniques is the main subject of this paper.

2. Ultrasonic inspection

Ultrasonic pigs are equipped with sensors known as ultrasonic transducers. These transducers are responsible for sending an ultrasonic pulse, and receiving echoes of this pulse. Figure 1 shows a typical ultrasonic pig. Its structure includes rubber disks to support the cylindrical body. Actuating on these disks, the transported fluid pushes the pig along the pipeline. The cylindrical body houses the electronic circuits and batteries. An odometer is used to determinate the position of the pig inside the pipeline.

The transducers fire ultrasonic pulses toward the pipeline wall and receive the echoes originated at the wall. When an ultrasonic pulse reaches the wall, its energy is divided, with one part being reflected (generating the first echo), and the

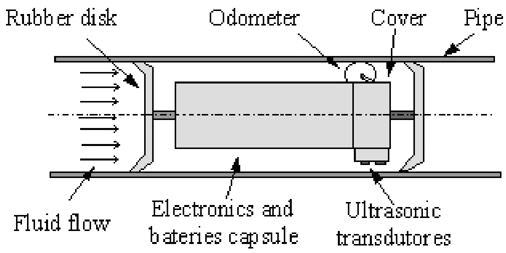


Figure 1. A pig inside a pipeline

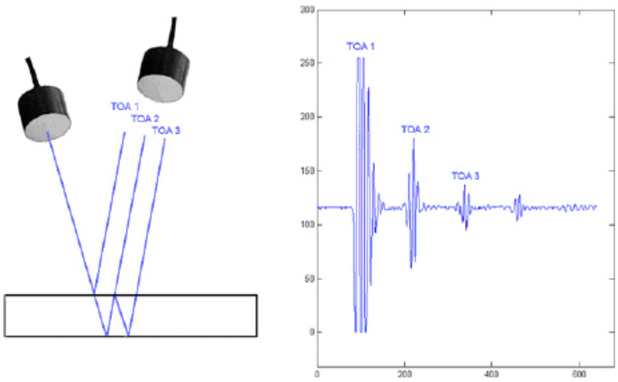


Figure 2. Ultrasound emitted pulse, and its echoes, determining multiple TOAs

other part being transmitted into the metal of the wall. When the transmitted energy reaches the second interface of the wall, it is reflected back against the first interface.

Figure 2 shows an example of sending and receiving an ultrasonic pulse (two transducers are displayed to better illustrate the echo generation process, but in practice just one transducer is used to send and receive the ultrasonic pulses). Following the first echo, the received signal shows the echoes that are generated by the multiple reflections that take place inside the metallic wall. Knowing the speed of the acoustic wave in each medium, and measuring the time between the emission of the signal and the reception of the echoes (known as TOA - Time of Arrival), it is possible to determinate the distance traveled by the signal. This technique is known as pulse-echo.

The TOA of the first echo gives the distance between the transducers and the wall. Using a ring of transducers and taking successive measures, it is possible to reconstruct the surface profile of the internal wall. Using the time delay between the first and the second echoes, the wall thickness can be determined.

So, the basic problem is to correctly estimate the TOA of the received echoes. Echoes reflected from clean, plain surfaces are well behaved, like the signal seen in Fig. 2 for example. However, when the surface is irregular and corroded, the presence of the echoes in the received signal is not clearly determined.

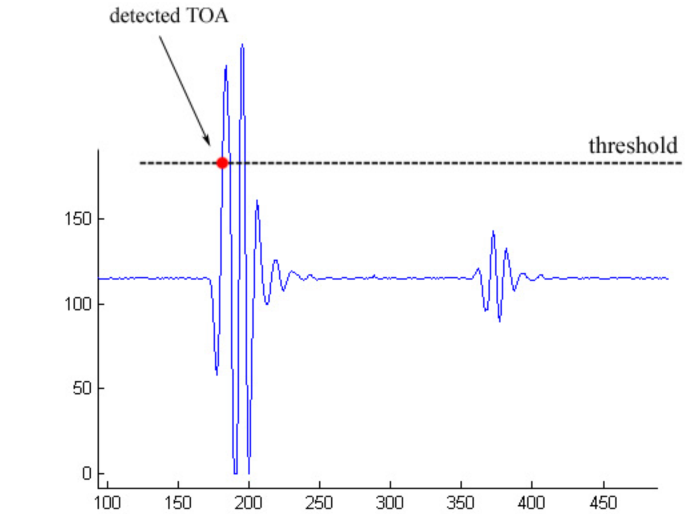
Nowadays, a common TOA estimation method uses a simple, analog processing technique. The received signal is input to a threshold detector, and the time when its amplitude reaches a determinate value (the threshold) for the first time is considered the first TOA. This approach is subject to several sources of errors. The detection depends directly to the amplification gain of the receiving circuit: a lower gain will produce signals that never reach the threshold; with a higher gain, noise can be detected as an echo by mistake. Also, it is very difficult to adjust a second threshold detector to find the second echo, since it has to be activated only after the energy of the first echo has faded away. Figure 3 illustrates these different problems.

In this work, it is proposed an approach based on Digital Signal Processing (DSP) techniques. The received signal is digitalized using a fast A/D converter and the TOA is estimated using the instant of the largest peak of the echo signal. This method will be explained in details in the following section. Signal processing is performed via dedicated hardware in real-time, avoiding the need of storing the complete signal, and only TOA estimations are stored in memory.

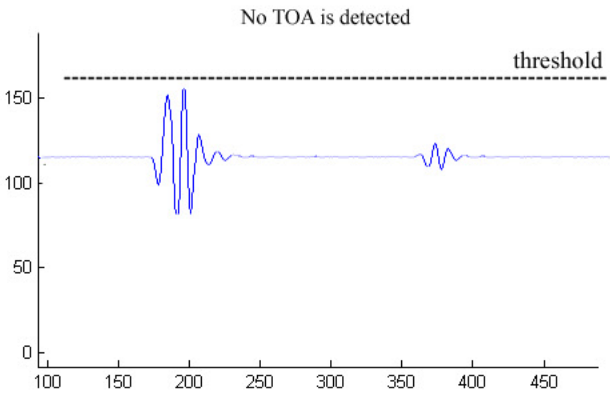
3. Developed Hardware

The advantage of using DSP hardware, instead of software, is that signal processing can be made in *real-time*, and only the results (the information that really matters) can be stored. Even modern micro-processors are not fast enough to process in real-time ultrasonic signals that are acquired at 50 to 100 MS/s (considering a 1 to 10 MHz ultrasonic transducers).

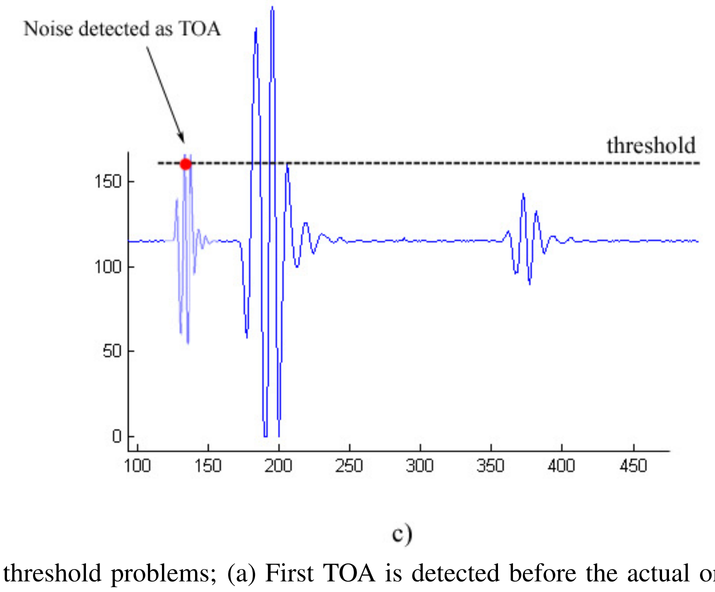
In applications such as ultrasonic pigs, storage capacity is really important, because physical space is limited, as long



a)



b)



c)

Figure 3. Examples of threshold problems; (a) First TOA is detected before the actual one; (b) Low amplitude signal does not reaches the threshold – no TOA is detected; (c) Noise triggers the threshold detector. In all cases it is difficult to detected the second echo – a lower threshold has to be used, that can be fooled by noise or by the tail of the first echo.

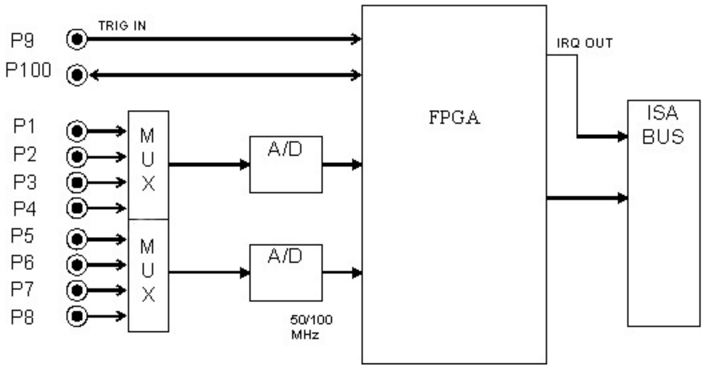


Figure 4. Block Diagram of the UADP

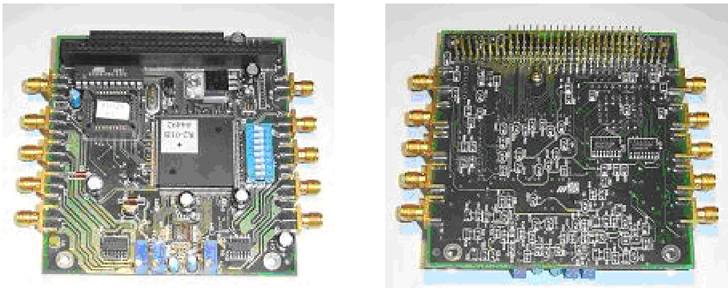


Figure 5. Photos from the developed module

as energy supply. The device have to operate for long periods and for this reason too much information would have to be stored, if not processed in acquisition time.

To implement the DSP hardware, an Ultrasound Acquisition and Digital Processing (UADP) module has been developed. The UADP module consists of the following basic elements:

- Fast 8-bit resolution A/D converter, with 50 or 100 MHz sampling rate.
- 8 input channels divided in two 2 banks of 4 channels. Simultaneous acquisition of two channels (one in each bank).
- Trigger In and Trigger Out channels.
- Analog multiplexer in each bank of channels.
- A standard 16-bit PC-104 ISA bus.
- An FPGA (Field programmable gate array, a high density programmable device) with access to the ISA bus.

The UADP module was designed using the PC-104 standard bus and dimensions (96x91 mm) (PC/104 Embeded-Pc modules, 2003). So it can be directly connected to this standard embedded computer.

The module is divided into two main units: the acquisition unit, and the processing unit. The acquisition unit consists of the input channels, triggers and A/D converters. The FPGA chip constitutes the processing unit, where digital circuits are implemented to store and to process the signal samples. The module is controlled via the ISA bus by a PC-104 computer board, which runs the operating system and custom programs developed in C language.

Figure 4 shows a block diagram of how the components are related to each other, and Fig. 5 shows the UADP module.

The FPGA can be easily reconfigured, what makes really easy, fast and cheap to implement new circuits in the module. So, for testing a new digital processing algorithm, all that is needed is to translate it into a digital the circuit and download it into the configuration memory of the FPGA. With this approach, many different DSP techniques can be tested without the need of making new boards and circuits. Also, corrections can be easily made when debugging the DSP algorithms.

4. Peak Detection

The idea behind the proposed detection algorithm is to detect envelope peaks of the signal, and use their instants as TOA estimates of the echoes. The time instant associated to largest value of the signal is adopted as the TOA estimate of the first echo, since there is a good correlation between them.

The TOA of the second echo is associated to an envelope peak that follows the largest peak. As this second peak is usually smaller in amplitude than the tail of the first echo, a time windowing algorithm must be used.

The algorithm was developed with the following programmable parameters:

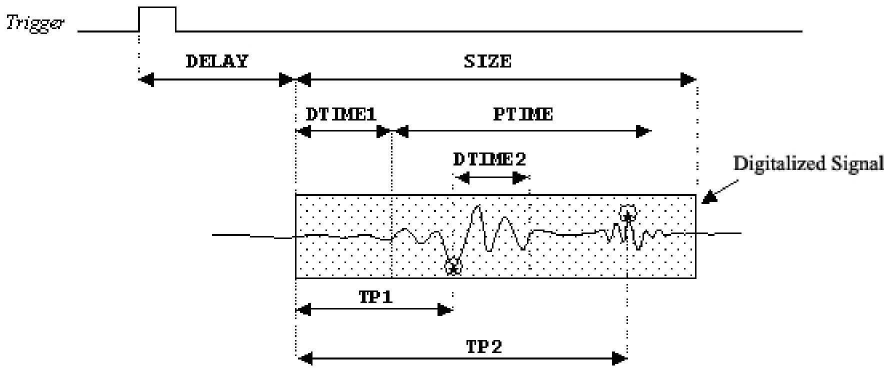


Figure 6. Peak detector programmable parameters

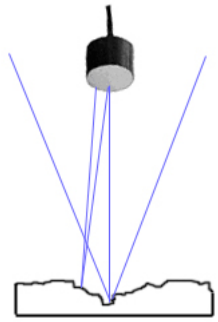


Figure 7. Ultrasound signal being dispersed in the corroded area

- DELAY - Delay between the trigger and the acquisition start
- SIZE - Number of samples
- DTIME1 - Dead time between the acquisition start and the activation of the first peak detector
- PTIME - Peak detectors actuation time
- DTIME2 - Dead time between the first peak detector and the activation of the second peak detector

It is also possible to individually configure the first and the second peak detectors to look for positive or negative values. This feature was implemented because usually the first echo is out of phase compared to the other echoes. In other words, the first echo is generated with phase inversion at the interface between a fluid and the internal pipeline wall, and the second echo is generated without phase inversion when the acoustic impedance of the metal of the wall is higher than that of the medium outside the pipeline (in most cases, it is).

Figure 6 shows an example of a signal with all the algorithm parameters. Detected TOA instants are indicated by TP1 and TP2. With this technique, TOA detection is not likely to fail on low energy signals as it occurs with threshold detectors, because the criterion is related to the maximum energy of the signal (the biggest peak always can be detected). The criterion does not fail to produce TOA estimates, but can lead to false estimates.

Corroded and irregular surfaces can disperse the ultrasonic wave front, reducing the energy that reaches the transducer back. On the other hand, the ultrasonic energy is not concentrated like a laser beam, and its beam aperture can be large enough to irradiate lateral structures that send strong echoes back to the transducer. These problems are illustrated in Fig. 7.

Strong lateral echoes can overcome dispersed, low amplitude echoes, leading to wrong first TOA estimates. When that occurs, not only a wrong point of the surface profile results, but also the thickness measurement is compromised. Even when the first TOA is not affected, lateral echoes can mask the signal of the second echo, which usually has amplitudes much lower than the first echo. Electronic noise can also make difficult to find the correct echo arrival instants on low amplitude signals.

5. Tests and Results

The system was tested using a flattened piece of a corroded pipeline. Figure 8 shows the test specimen. In order to get its correct dimensions, the specimen was scanned in a Mitutoyo BN710 3D coordinate measuring machine (Japan), along the drawn lines visible on Fig. 8 and between them.

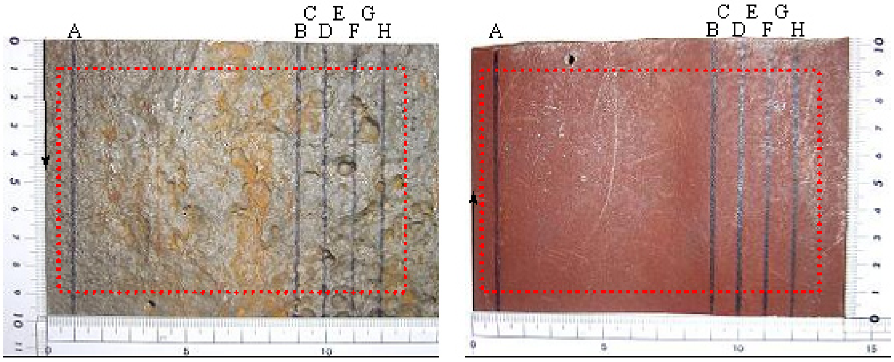


Figure 8. Peace of pipeline used as test specimen; at left, the (corroded) internal face; at right, the external face.

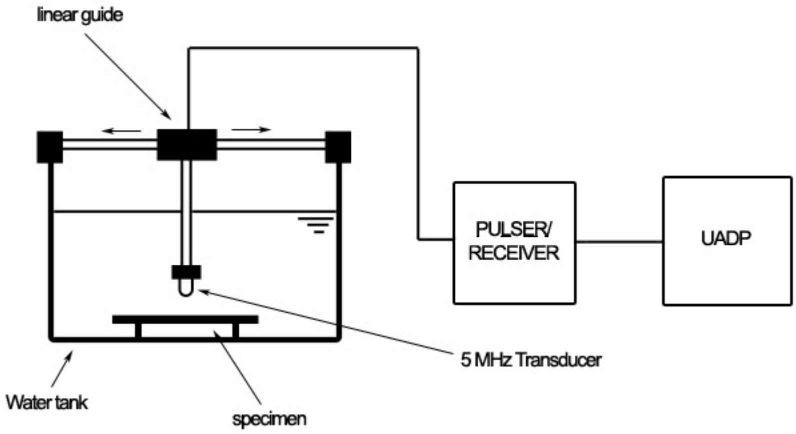


Figure 9. Experimental Setup

The same lines were scanned with the UADP module using one non-focused, broad-band ultrasonic transducer (KB Aerotech ALPHA, USA, 5 MHz nominal frequency, 0.25 in diameter). A Panametrics NDT 5072PR pulser/receiver (USA) was used to excite the transducer and to amplify the received signal, that was acquired and processed by the UADP module. Signals were sampled at 50 MS/s (20 ns sampling period).

The specimen was horizontally placed in a water tank and the transducer was moved along horizontal pathes above the lines, mounted on a linear guide to keep it at a fixed distance from the specimen. Figure 9 illustrates the experimental setup.

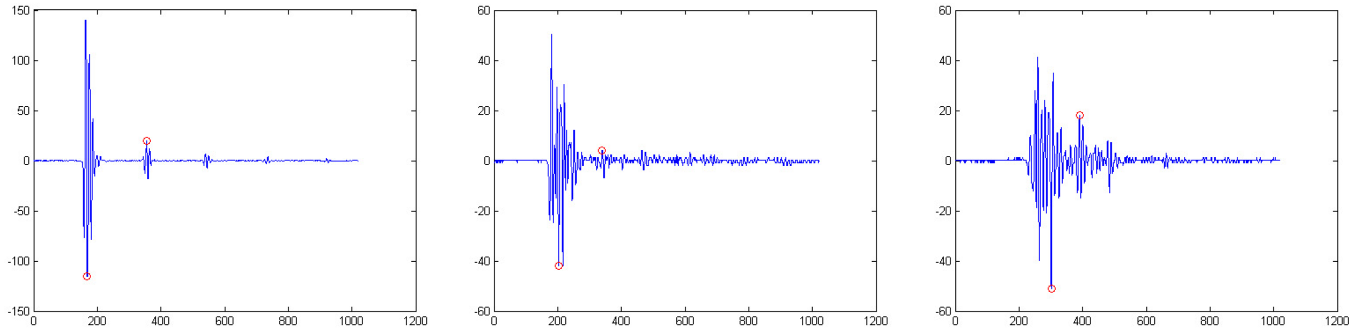
Figure 10 shows examples of acquired signals and detected peaks. Amplitudes are given in integer numbers, produced by the UADP's 8-bit A/D converter. The first detector was configured to look for negative peaks, and the second detector was activated after 1.6 us (DTIME2 = 80 samples) from the first peak detection instant. Detected peaks are indicated by the small red circles.

The first signal (a) corresponds to the echo obtained at position 35 mm on the scanned line A. This region presents low corrosion level, and the resulting signal has high amplitudes and good S/N ratio, so the first and second TOA can be clearly determined.

The signal shown in Fig. 10 (b) corresponds to position 55 mm on line F, which lays on a corroded region. Amplitudes are smaller, and the envelope of the first echo can not be clearly distinguished, with many peaks that could correspond to the first TOA. The last signal (c) was acquired at position 47.5 mm of line F. In this region the wall thickness is very reduced due to the presence of a large pit, so the time delay between the first and the second echo is not large, and it is not easy to separate them.

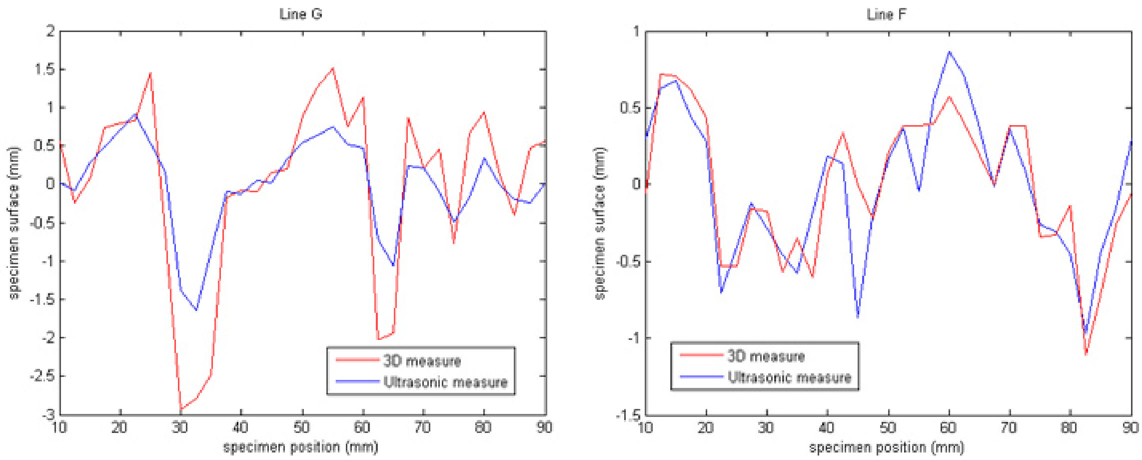
Furthermore, Fig. 10 also shows that the correct estimation of the second TOA strongly depends on an adequate choice for the parameter DTIME2, which controls the dead time after the detection of the largest peak: a short dead time will make the second peak detector be triggered during the tail of the first echo; a long one will cause the miss of the second echo. Consequently, the use of broad band or highly dumped transducers are desirable to produce short duration ultrasonic pulses for measuring thin pipeline walls.

Figure 11 shows the resulting surface profiles along lines G and F, which cross a region with many corrosion pits. For comparison, the mechanically measured profiles (red curves) and the ultrasonic scan results (blue curves) were rotated to stay horizontally aligned, setting the first and the last points of each curve to the same value, and than the curves



a) b) c)

Figure 10. (a) Signal with good S/N ratio, resulting in a good detection of the TOAs; (b) and (c) Weak signals, resulting in unreliable TOA estimations



a) b)

Figure 11. Surface reconstruction using with 3D machine (red) and ultrasound (blue) of: (a) Line G and; (b) Line F of the specimen

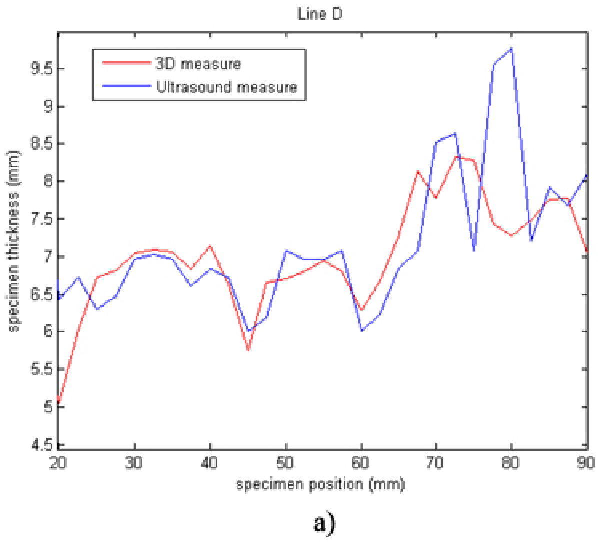
were offset to have null mean value. The water path corresponds to the region above the curves, so negative distances corresponds to corrosion pits on the specimen, and positive values correspond to less corroded areas (metal of the wall).

Even with some discrepancies the drawn surfaces are very close. Figure 11(a) clearly shows the effect of the aperture of ultrasonic beam (about 5 mm at focal point), which limits the lateral resolution of the scan. Pits (at positions 30 and 65 mm) and protuberances (positions 25 and 55 mm) are flattened out in the reconstructed profile. Figure 11(b) shows points were the largest-peak criterion failed in estimating the TOA of first echo, at positions 55 mm and 47.5 mm, due to echoes from different paths that have summed up at the transducer, as one can see on Fig. 10(b) and (c).

Figure 12 shows the scan results for the thickness measurement along lines D and F. Line D crosses a corroded region without pits. Position 75 mm in Fig. 12(a) corresponds to a spurious high amplitude point of the signal that was detected as the second TOA before the correct echo. Position 85 mm in the same curve corresponds to a wrong peak detected after the second echo. These problems can be found more times on Fig. 12(b), since line F lays on a very corroded area of the specimen.

In these corroded areas, S/N ratio of the second echo's signal is very poor, and the detection of the echoes is more prone to errors. Furthermore, comparing the curves related to the first and second TOA estimates along the scanned line F (Fig. 11(b) and 12(b)) at positions 55 and 47.5 mm, it is possible to see that, when the first detection fails, the second fails too. Again, refer to Fig. 10(b) and (c).

However, Table 1 shows that the mean of the thickness values that were measured with the ultrasonic system along the scanned lines are really close to the mean thickness computed using the values measured with the 3D machine.



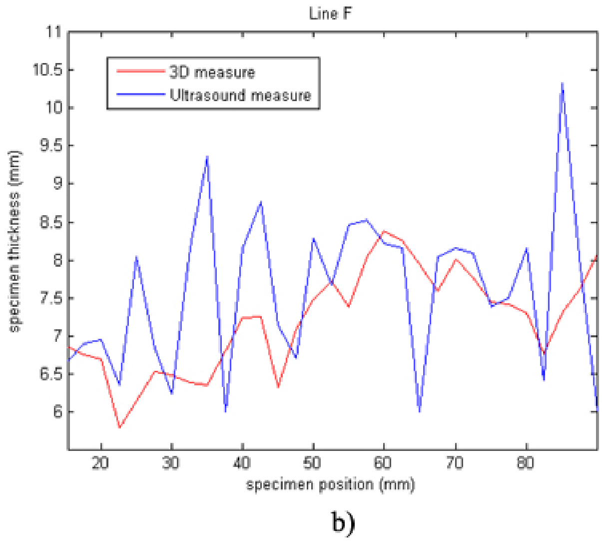


Figure 12. Thickness measure with 3D machine and ultrasound of: (a) Line D and; (b) Line F of the specimen

Table 1. Thickness results for both inspections

Line	3D mean Thickness	Ultrasound mean Thickness	Error
D	7,0187	7,1357	1,6%
F	7,2009	7,7207	7,2%

6. Conclusions

The developed Ultrasound Acquisition and Digital Processing module was capable of processing digitalized ultrasonic signals in real-time, at acquisition rates up to 100 MS/s. In laboratory, ultrasonic signals from 5 MHz transducers were correctly acquired, stored and processed.

In laboratory experiments, the system was used to scan a flattened piece of a real corroded pipeline with a 5 MHz ultrasonic transducer. The surface profile and the thickness of the specimen was measured using a precise 3D measuring machine in order to evaluate the precision of the measures produced by the ultrasonic system.

The hardware implementation of the peak detection algorithm produced accurate estimates of the TOA of the first echo, which is used to reconstruct the surface profile of the internal wall. The resolution of the reconstructed profile is directly limited by the aperture of the ultrasonic beam. Reconstructed surfaces showed good correlation with the profiles generated with the 3D machine, even on areas presenting intense corrosion.

On the other hand, the peak detection algorithm fails more often to correctly detect the TOA of the second echo, which is used to measure the thickness of the wall. The second echo has amplitudes much smaller than the ones of the first echo, and the second detector usually fails when the first detector does. These errors occurs frequently when strongly corroded surfaces are scanned, but experimental results showed a good agreement between the real and measured values in terms of the average thickness along 80 mm scanned lines.

Implementing DPS hardware on a FPGA constitutes a powerful approach. It was possible to perform fixes and improvements on the algorithms easily and at very low cost. Now it is possible to implement, test and compare more sophisticated algorithms using the same electronic module.

7. Acknowledgments

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