MONITORING OF CORROSION IN PIPES USING AN ARRAY OF ULTRASOUND TRANSDUCERS

Julio Cezar Adamowski, jcadamow@usp.br
Nicolas Perez, nico@fisica.edu.uy
Marcelo Yassunori Matuda, fbuiochi@usp.br
Flávio Buiochi, fbuiochi@usp.br
Alan T. Souza, souza.at@gmail.com
Department of Mechatronic and Mechanical Systems Engineering / University of São Paulo
Av. Prof. Mello Moraes, 2231, 05.508-030, São Paulo, SP, Brazil

Claudio S Camerini, claudio@petrobras.com.br
Carlos Patusco, patusco@petrobras.com.br
CENPES / Petrobras Research Center
Av. Horácio Macedo, 950, 21.941-915, Rio de Janeiro, RJ, Brazil

Abstract. *The most commonly used and widely accepted means of corrosion monitoring is the use of coupons introduced inside the pipe. An alternative approach is the use of ultrasonic technology which provides a nonintrusive monitoring of corrosion. Ultrasound techniques have been used successfully in the accurate measurement thickness. The round trip duration of propagation, divided by the known sound velocity through the pipe material, provides a wall thickness measurement equally accurate to a micrometer reading. Moderate rate corrosion of steel reduces the pipe wall thickness from 0.1 to 0.2 mm/year. Accurate measurement of thickness requires temperature adjustments for both the size and the velocity of propagation. This paper presents the development of a corrosion monitoring equipment using an array of ultrasonic transducers. The tests were performed to assess the stability and repeatability of the measurement technique. An experimental setup using eight 5 MHz ultrasonic transducers was mounted on a mechanical device which represents part of a 272-mm-in-diameter and 20-mm-thick pipe section. The device was immersed in water and the eight transducers were connected to a multiplexed ultrasound equipment, connected to a PC via USB interface. It was also used a digital USB thermometer (resolution of 0,01°C) connected to the same microcomputer. The signals from each ultrasound transducers and temperature measurements were acquired every 4 minutes for 60 days. The pipe thickness was measured using the travel time between two internal reflections using the Hilbert transform of the cross-correlation between two echo signals. Since there was a water delay line between the transducers and the outer wall of the pipe, the travel time was measured in this medium for each transducer. Several strategies can be used for temperature compensation; in this case the implicit function between the travel time in the water and the propagation time on the pipe wall is used to compensate temperature variations. From the pipe wall thickness measurements performed within 60 days of testing, appropriately correcting for temperature, it was found that the variation in the measured thickness of the pipe wall was less than 2 micrometers. This variation is due to existing noise in measurements, differences in temperature compensations and presence of sediment in long times. In order to check the level of detection, a sandpaper was used to induce a corrosion spot in the region in front of one of the transducers. After this procedure, the ultrasonic measurement detected a wall thickness decrease of approximately 25 micrometers. The developed technique has great potential for monitoring corrosion in oil pipelines. Currently, the technique is being extended to the development of a prototype for operation in deep waters, using 32 ultrasonic transducers, with capability of continuously monitoring for 2 years.*

Keywords*: ultrasonic array, corrosion detection, nondestructive testing*

1. INTRODUCTION

The most commonly used and widely accepted means of corrosion monitoring is the use of coupons introduced inside the pipe. Weight loss coupon monitoring is the oldest method for assessing the corrosivity of an environment on a specific material and involves exposing a specimen (coupon) of the material to the environment for a given duration, and measuring the resultant weight loss. It is an intrusive device and requires very expensive and time consuming manual intervention for installation and frequent retrievals and re-weighing for useful data to be obtained. An alternative approach is the use of ultrasonic technology which provides a nonintrusive monitoring of corrosion Rommetveit *et al*. (2008). Ultrasound techniques have been used successfully in the accurate measurement of thicknesses. The round trip duration of propagation, divided by the known sound velocity through the pipe material, provides a wall thickness measurement equally accurate to a micrometer reading. The main problem is that the sound velocity depends on the temperature. The corrosion monitoring of offshore deep water pipelines is still a challenge due to the difficulty of accessibility. Standalone systems are extremely convenient in terms of installation and price. These devices are typically self-contained battery powered data loggers with on-board data storage. The logger can be deployed and retrieved by ROV if required and brought back to the surface for downloading and refurbishment.

Moderate rate corrosion of steel reduces the pipe wall thickness in the order of 0.1 mm/year. The ultrasonic accurate measurement of thickness requires temperature adjustments for both pipe thickness and velocity of propagation Rommetveit *et al*. (2010). This paper presents the performance evaluation of a corrosion monitoring technique using an array of ultrasonic transducers and temperature compensation Rommetveit *et al*. (2010). Tests were performed to assess the stability and repeatability of the measurement technique using an experimental setup with eight 5-MHz ultrasonic transducers mounted on a mechanical device which represents part of a 250-mm-diameter 20-mm-thick pipe section. The paper presents the experimental setup, the signal processing technique used to achieve the best resolution, the temperature compensation strategies, the experimental results and the conclusions.

2. EXPERIMENTAL SETUP

In order to implement the test to evaluate the methodology a special sample is constructed. The main objectives of the present experiment are the evaluation of the limit of detection and the correction of temperature effects. Both evaluations can be made using a sample with the same geometry as a section of a pipe; in this case the dispositive is constructed using aluminum in order to simplify the manipulation.

Figure 1 shows two perspectives of the mechanical dispositive. Standard pipe geometry is selected for the test: diameter 272 mm and thickness = 20 mm. The dispositive is a slice of 50 mm and close to 1/6 of the pipe diameter.

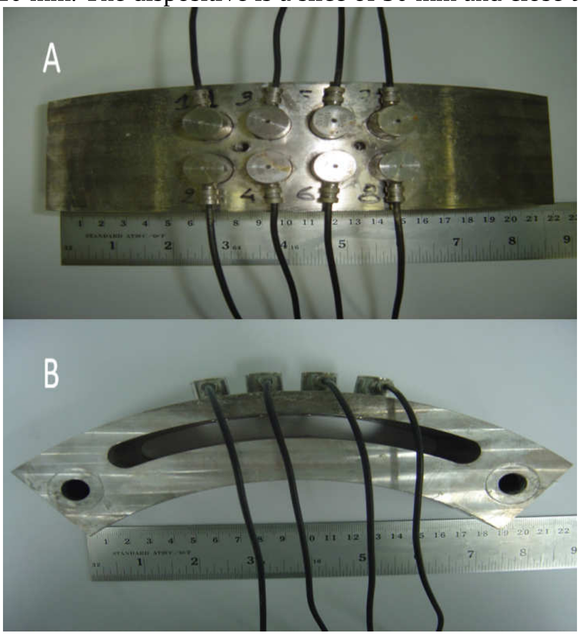

Figure 1. Mechanical dispositive and 5 MHz transducers. A) Upper view. B) Lateral view.

The sample is placed in a water tank in order to couple the surface of the sample with an array of ultrasonic transducers. The signals are emitted and received by eight 5 MHz ultrasonic transducers. These transducers were developed in the *"Escola Politécnica da Universidade de São Paulo"* for high pressure applications. In Fig. 1.B there is a gap between the transducers and the external surface of the pipe, this gap corresponds to the first echo arriving time.

A 16 channel ultrasonic pulser/receiver was used to send and receive the signals, at the same time the temperature is measured in two different points of the water tank. Is noted that the temperature is not controlled and it varies freely along the day. Both the pulser/receiver and the thermometer are controlled by an acquisition PC running Matlab.

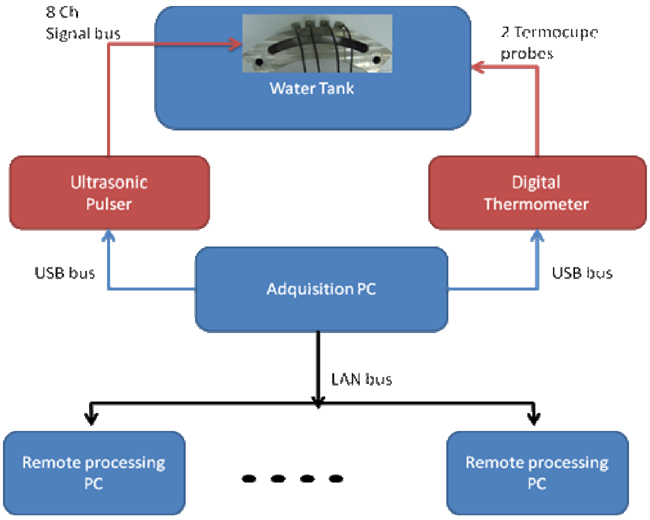

Figure 2. Schematic diagram

The software in the acquisition PC record the 8 ultrasonic signals, the 2 temperatures and the real date and time of the acquisition. This data is recorded and stored in a shared file, one file is generated every four minutes.

Using this architecture, the data signal processing and visualization can be made in several remote PC's without interfering with the acquisition.

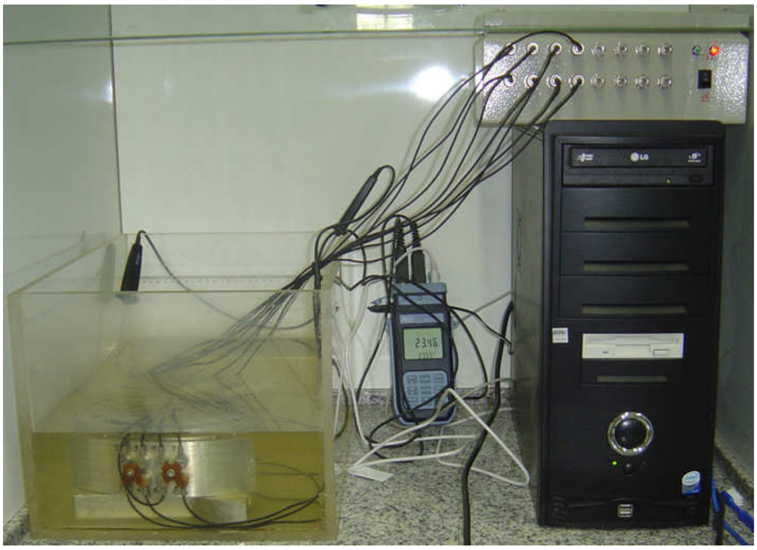

Figure 3. Experimental Setup.

3. SIGNAL PROCESSING

In this section the main features of signal processing are presented. To evaluate the corrosion level in the tube, the time of flight of ultrasonic pulses propagating inside the tube is used. The time interval considered in the received ultrasonic signal includes the first three echoes; the first one is the reflection at the external surface, while the second and third are internal reflections.

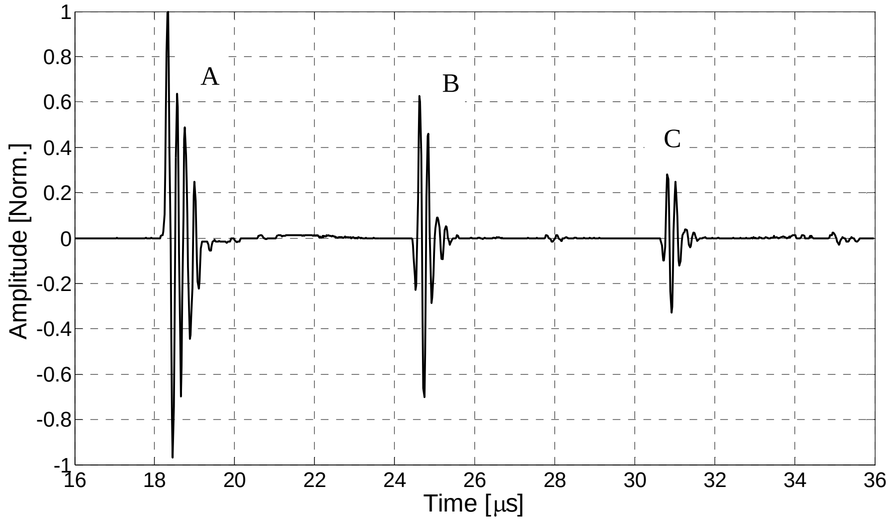

Figure 4. Ultrasonic echoes form the tube. A) First echo, reflection in the external wall of the tube. B) Second echo, first internal reflection. C) Third echo, second internal reflection

The time of flight of the first echo is used to evaluate the distance between the transducer and the tube. However, temperature strongly affects the results, as it changes the speed of the ultrasound both in water and in the tube. In the next section, this first echo is used to compensate the errors induced by temperature shifts.

The other time to be determined is T_T, the time between the second and the third echo. During this time, the ultrasonic pulse travels two times inside the sample, and if the speed of sound c_T in the tube is known, the thickness can be calculated by

$$Thickness = \frac{c_T \cdot T_T}{2}$$

The first step in the signal processing is selecting an appropriate temporal window for each echo; in this case it is simple because the echoes are not overlapping. In practice, the windowing is made by multiplying the signal by a rectangular pulse, centered in the maximum of the absolute value of the signal around the desired echo.

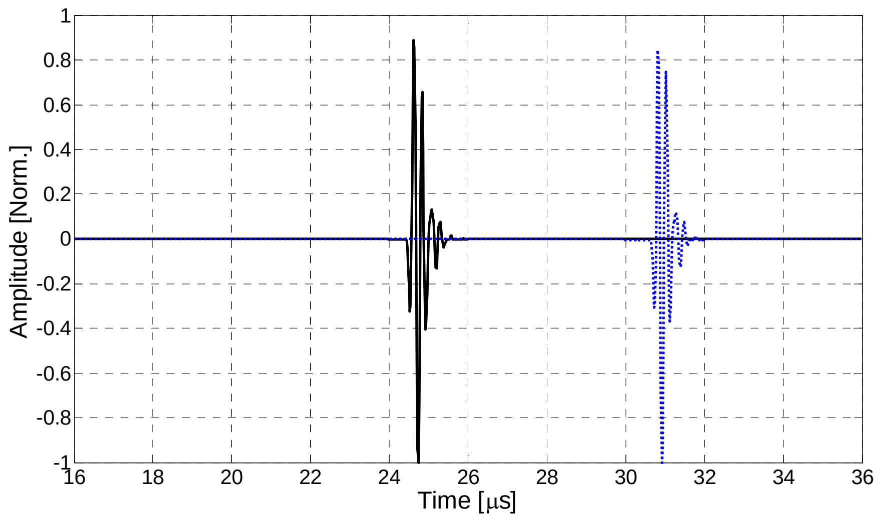

Figure 5. Windowing of second and third echoes.

Next, the cross-correlation of these two echoes E_1 and E_2 is computed. This can be calculated using the "*xcorr*" Matlab function or by using the Fourier transform $\mathfrak{F}$

$$C_{orr} = \mathfrak{F}^{-1}(\mathfrak{F}(E_1) \cdot \mathfrak{F}(E_2)^*)$$

For pulsed signals with similar shape, the *Corr* function is a symmetric and concentrated pulse. The maximum of this pulse is at the delay time between these two echoes. However, the determination of a maximum is a bit inaccurate.

One alternative is the use of the Hilbert transform; this function crosses zero at the maximum of the original function (Oppenheim and Schafer, 1998). The determination of a zero crossing is simpler than the determination of a maximum.

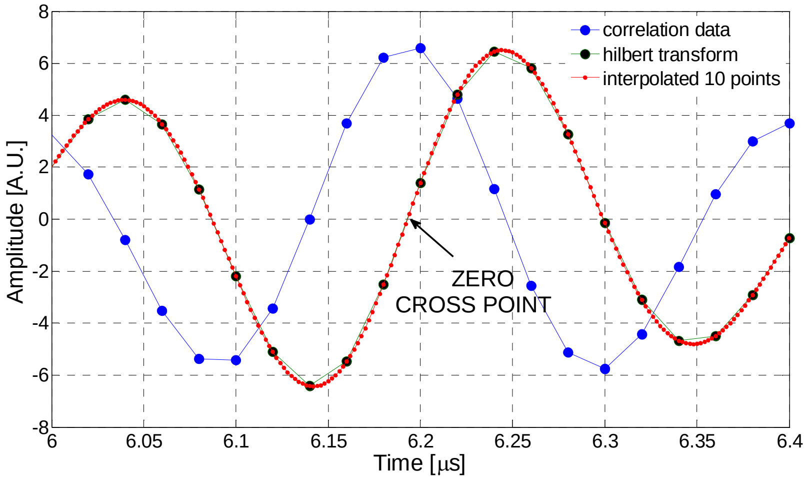

Figure 6. Cross correlation "Blue", imaginary part of Hilbert transform "dotted black", ten point interpolation of the Hilbert transform "dotted red"

At this point the determination of the transit time T_T is limited by the sampling frequency f_s used in the acquisition of the signals. In this case $f_s = 50\ MHz$, corresponding to a resolution of *20 ns* in the determination of the time and up to *60 µm* in the determination of the thickness. To reduce this limit an interpolation method must be used. In this case a low pass interpolation is used. This interpolation can be obtained by the use of the *"interp"* Matlab function or by taking the Fourier transform, extending the transform filling the high frequencies with zeros and calculating the inverse Fourier transform of the extended function. This interpolation results in the same spectrum as the original in the sampled region in the spectrum and zero amplitude for higher frequencies, for that reason it is called as low pass interpolation (IEEE, 1979). Figure 6 shows the results using ten interpolation points to illustrate the technique, but in practice a fifty point interpolation has been used to reduce the resolution to near 1 µm.

4. TEMPERATURE COMPENSATION

In order to achieve a high resolution in the thickness measurement, the temperature effects in the speed of sound must be compensated Rommetveit *et al*. (2010). To show this effect, the time of flight inside the tube T_T, the time of flight in water T_w and the temperature is displayed in a one week window.

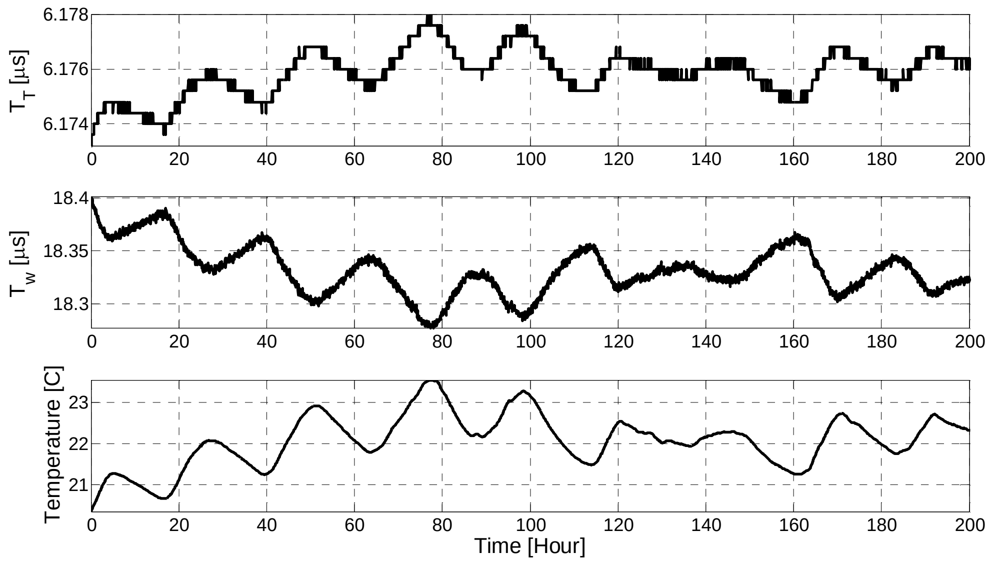

Figure 7. Evolution of the time of flight inside the tube T_T (A), Water time of flight (B) and the temperature (C) in one week.

One possible solution to reduce the fluctuation in the measurement is taking the mean value in a desired temporal window. The length of this window depends on the periodicity of the temperature variations, for which a quasiperiodic daily variation plus a slow drift is expected.

The sample acquisition rate is one complete set of measurements for each four minutes; one set is composed by eight ultrasonic channels and two temperature channels. The samples can be averaged over different temporal windows, for example over 1 sample (4 minutes), 15 samples (one hour), 60 samples (four hours) and 360 samples (24 hours).

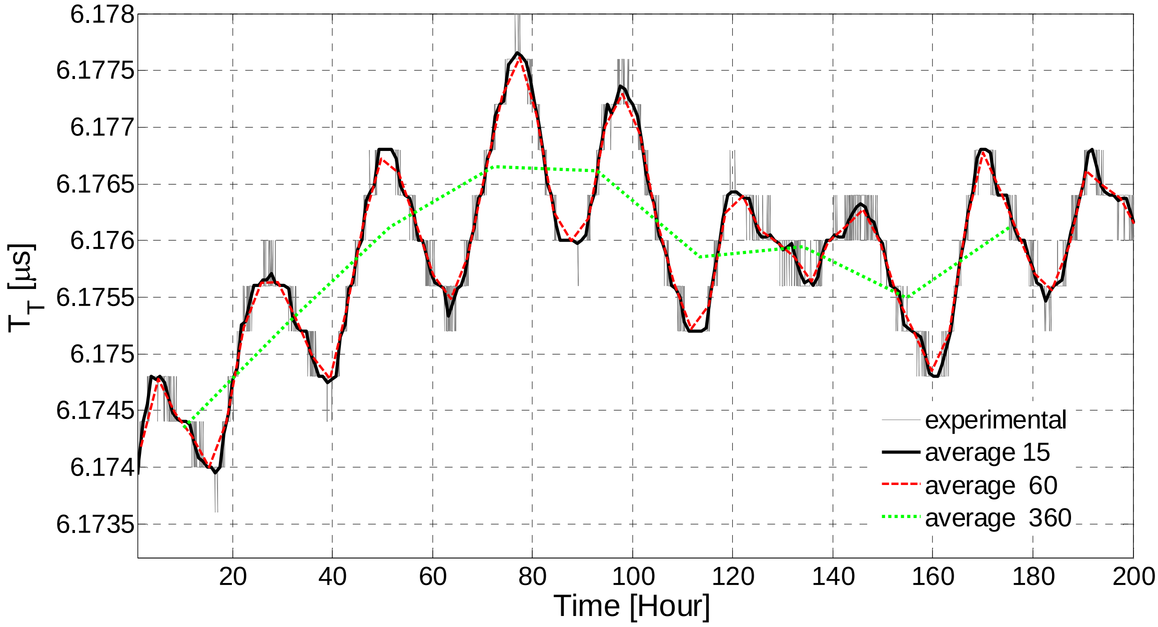

Figure 8. Averaging in the time of flight inside the sample. Continuous gray 1 sample, continuous black 15 samples, dashed red 60 samples, dotted green 360 samples.

Using an estimated value for the speed of sound inside the aluminum sample of *6350 m/s*, one division in the vertical axis in Fig. 8. corresponds to *1.5 µm*. As expected the use of averaging reduces the fluctuations due to temperature, however this strategy is limited by the long term drifts. To reduce such fluctuations, a very long term average must be used. In the proposed application, the desired resolution is in the order of *1 µm*, limiting the use of very long windows to achieve the desired resolution.

Thus, another temperature compensation schema must be used. One possibility is compensating the changes using an explicit law for the dependence between the speed of sound in the used material and the temperature. This law can be measured in laboratory with high precision. In this case, the temperature of the water must be also measured during the experiment and it is assumed that this temperature is the same as the sample temperature.

In this work an alternative methodology is used. This methodology is based in the existence of an implicit function between the time of flight inside the tube T_T and the time of flight in the water T_w. This dependence can be observed in the Fig. 7; when the temperature increases, the time in the water decreases and the time of flight inside the sample increases.

As the corrosion rate is very slow, it is assumed as a hypothesis that the tube thickness e is constant in a period of few days. In the case of our experiment this is strictly true because there is no real corrosion in the tube and the changes in the thickness are introduced in a controlled way using sand paper. Additionally, to reduce the influence of sediment deposits, all surfaces were cleaned using a small brush during the first week. This hypothesis allows obtaining a polynomial expression for the speed in the sample c_T as a function of the time in the water T_w.

$$T_s(k) = T_s\left(T_w(k)\right)$$

$$c_T(k) = \frac{2 \cdot e}{T_T\left(T_w(k)\right)}$$

Here the index $k = 1{:}Ns$ is the number of the sample. To estimate the value of the thickness e the measured speed in the tube at a temperature of *22 °C* is used (c_T=*6380 m/s*).

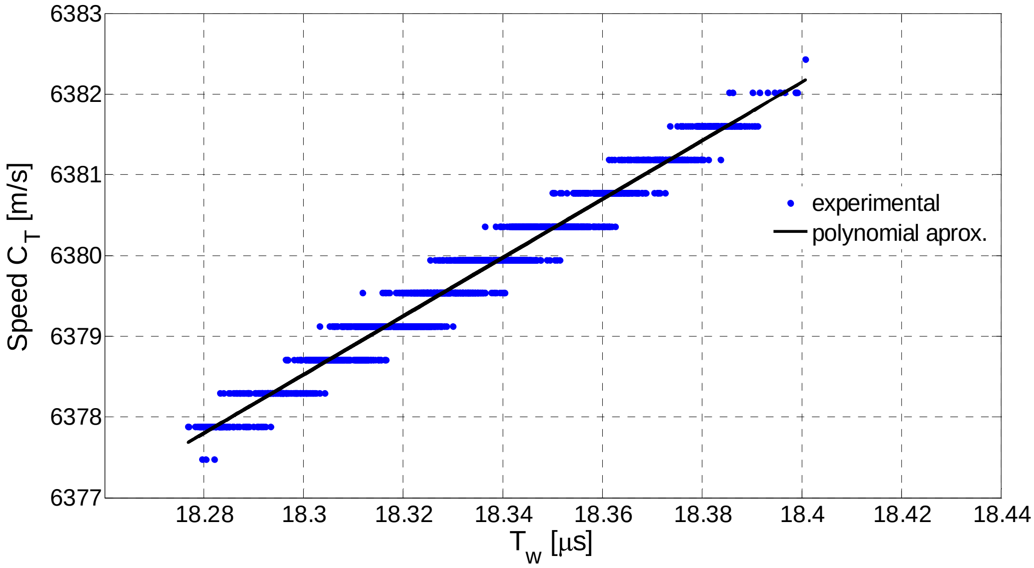

Figure 9. Relation between the speed of sound in the tube and the time of flight in water. Experimental data "dotted blue", polynomial approximation "continuous black"

As can be seen in Fig. 9, this relation can be approximated by a low order polynomial. This approximation is made channel by channel, that means one polynomial for the transducer in channel one, other polynomial for the transducer in channel two and so on.

In this example the speed of sound can be estimated as a function of the time of flight in water for the channel 1 as

$$c_T(T_w) = 3.6\ 10^7\ \mathrm{T_w} + 5.7\ 10^3$$

Using this corrected speed, the time of flight inside the tube becomes independent of the temperature, at least in the range used to adjust the polynomial. An important point to be verified is the efficiency of the correction for long times; Fig 10 shows the first *200 h* window used for the calculus of the polynomial adjustment and the same window after *1000 h*. Note that the drift in the thickness is less than *2 μm*, an acceptable value in this application.

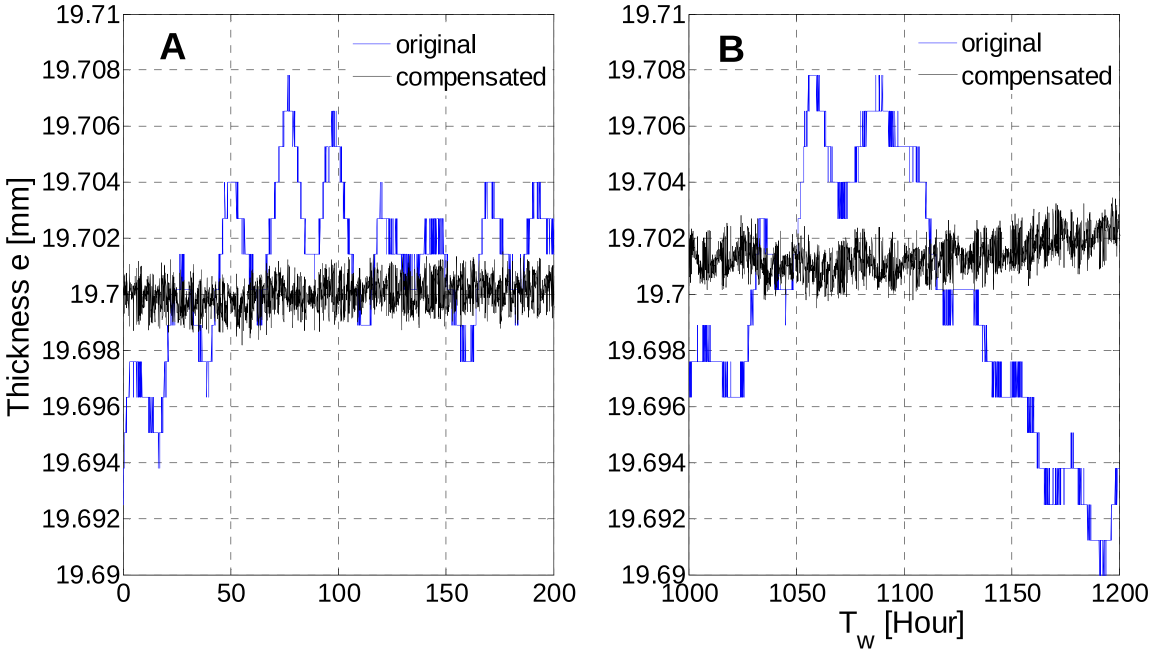

Figure 10. Temperature corrections in the thickness measures. A) first 200 hr. B) results after 1000 hr in continuous operation. Original data "blue line", temperature compensated data "black line".

The small drifts in the values for long times can be explained by the presence of sediments in the surfaces. This effect can be corrected using a safe reference, in this example channel 1 is selected as reference and the estimated sedimentation rate is *40 nm/day*. This can be observed in fig. 10*, 1000 h* corresponds approximately to 40 days and the predicted drift is *1.7* μm.

5. RESULTS

To evaluate the performance of the proposed system, continuous measurements were performed for sixty days. The measurement period is 4 minutes; this period is very fast for a corrosion process, but was chosen to evaluate the use of averaging in the results.

Each measurement set is composed by eight signals, one from each transducer. Each individual signal has 1000 points sampled at *50 MHz* using a 10 bit A/D converter. Additionally the temperature is measured in two different points in the bath.

After the first thirty days, a reduction in the thickness was made using sandpaper in front of the transducers numbered seven and eight. The sanding is higher in front of the transducer numbered seven; this evaluation is qualitative based in the polish time for each position.

The first results to be presented are the thicknesses measured from the echoes without temperature compensation, in order to show more details only channels 1, 2, 7 and 8 are displayed. Fig 11. show these results using a fixed speed in the tube of c_T= *6380 m/s*. Additionally, the data are presented in three windows, the first corresponding to the first five days (remember that the temperature compensation is made using the first week data), the second window corresponds to the five days period around the moment in which the sample is polished and the last window corresponds to the last five days. To evaluate the possibility of detecting changes in long times, the first and the last window must be compared. The center window evaluated the detection of a localized jump.

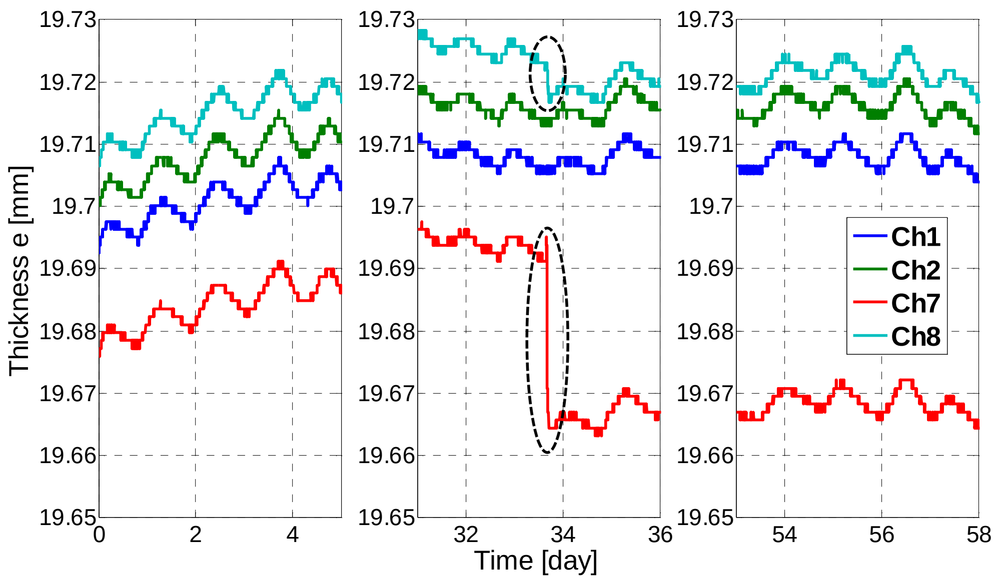

Figure 11. Measured thickness in channels 1, 2, 7 and 8 without temperature compensation. Dotted ellipses show the jumps produced by polishing.

As expected, the temperature drifts disturbes the measurements; big changes like the observed in channel 7 are detectable without compensation in a localized jump. However, for long times and continuous process it is difficult to determine changes in the order of tens of microns. Little changes like the induced in channel 8 are imposible to detect for long times and also difficult to detect in the moment of the jump.

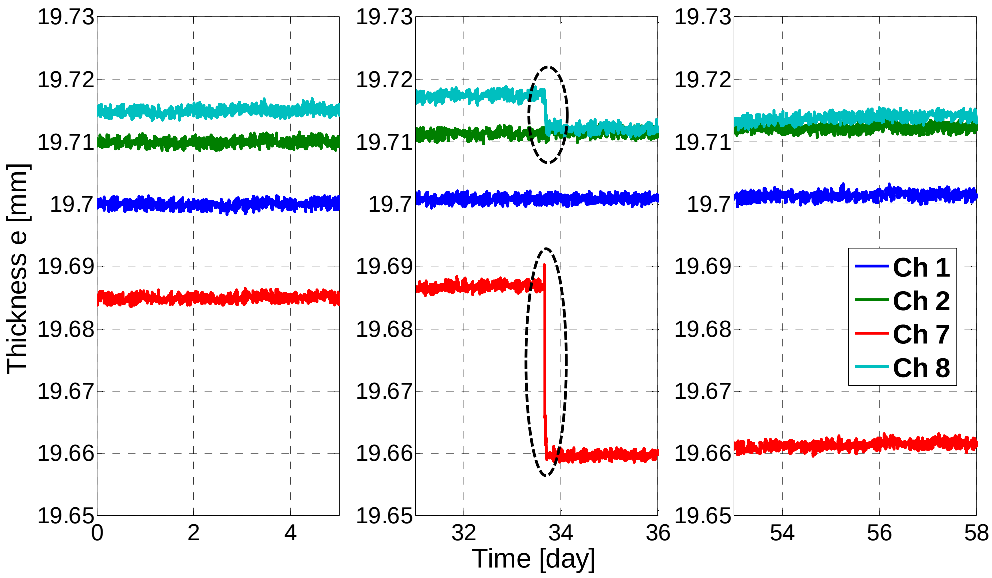

Figure 12. Data corrected by temperature using the time of flight in water.

When the speed of sound is compensated by temperature, the fluctuation of the data is greatly reduced. In this case fluctuations in the order of tens of micrometers are easily detected for long times, as shown in Fig. 12. Both jumps are also detected; a *5μm* jump is estimated in the case of channel 8 and a *25 μm* jump in the case of channel 7. However, little changes can be masked by sedimentation for long times.

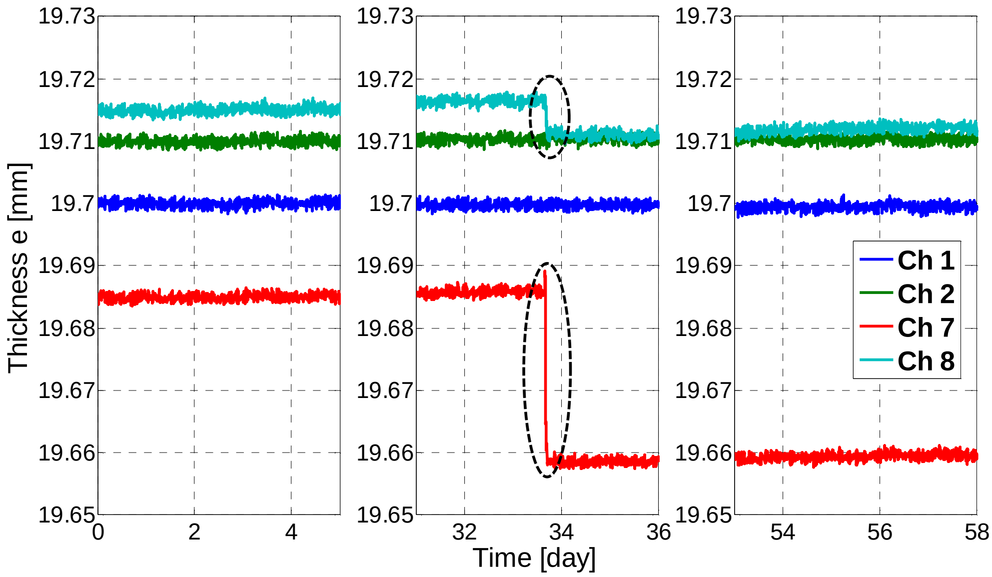

Figure 13. Data corrected by temperature and sedimentation rate.

In this example the drift in channel 1 is used to estimate a rate of sedimentation and all channels are compensated using this value. Although this compensation is imperfect, it may improve the results, as shown in Fig. 13, and can be easily implemented by placing a reference body in parallel with the real measure.

6. CONCLUSIONS

In this work is evaluated an ultrasonic system for corrosion monitoring in pipelines. The use of *5 MHz* transducers sampled at *50 MHz* allows achieving a resolution in the order of *1 μm*. The distance between the transducer and the tube can be calculated using the first echo (see Fig. 4) and the thickness is calculated using the time between the second and the third echo.

To calculate the times a cross-correlation algorithm is used, additionally to obtain the desired resolution an interpolation schema is needed. To obtain a resolution near of *1 μm*, a *50* points interpolation is needed.

In the case of an underwater application two aspects must be considered, the energy consumption and the amount of memory available onboard. To both factors the number of measures must small as possible, in Fig. 8. can be seen that using one measure each hour the dairy variations can be followed and corrected a posteriori. The use of average in an individual measure to reduce the noise must be evaluated in the final application, because it depends strongly on the used electronics, the presence of impurities in the water and the quality of the external surface.
Temperature effects can be corrected in posprocessing using the time of flight in water. However in real applications the temperature inside the tube can be different from the temperature in the water. At this moment a new experiment is planned to evaluate the compensation in the case of different temperatures. The presence of sediments also affects the results; this can be corrected using an external test body safe of corrosion and internal temperature.
The mechanical setup is critical in this application; all transducers must remain fixing during the experiment. In the design of the mechanical setup the distance between the transducers and the pipeline surface should allow the collection of the first three echoes without interference.
As can be seen in the results, changes in thickness in the order of hundred micrometers are easily detected even over month variations. Using an adequate temperature compensation schema variations of tens micrometers can also detected. To determinate variations less than ten micrometers the sedimentation must be compensate, this effect also depends strongly on the real application conditions and must be evaluate in the future with more precision.

7. ACKNOWLEDGMENTS

The authors would like to thank PETROBRAS/ANP, FAPESP and CNPq for the financial support that make this work possible.

8. REFERENCES

IEEE, 1979, “Programs for Digital Signal Processing”, IEEE.
Oppenheim, A.V., and Schafer, R.W., 1998, “Discrete-Time Signal Processing”, 2nd ed., Prentice-Hall.
Rommetveit, T. Johansen, T.F., Baltzersen, O., 2008, “Using ultrasound measurement for real-time process control of pipelines and process equipment subjected to corrosion and/or erosion”, Paper 08285 NACE Corrosion 2008.
Rommetveit, T. Johansen, T.F., Johsen, R., 2010, “A combined approach for high-resolution corrosion monitoring and temperature compensantion using ultrasound”, IEEE Transac. On Instrumentation and Measurement, vol. 59, no. 11, pp. 2843-2853.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.