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6

Fouling Detection Based on Parameter Estimation

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1. Introduction

A severe problem that may occur when fluids are transported in duct systems and pipelines is the slow accumulation of organic or inorganic substances along the inner surface over time. Such accumulation of unwanted material is denoted fouling, and occasionally appears simultaneously with tube corrosion. Both, fouling and corrosion are major concerns for plant operation and lifetime in chemical, petroleum, food and pharmaceutical industries, due to the detrimental impact of such phenomenon on the reliability and security (Rose, 1995), (Cam et al., 2002), (Hay & Rose, 2003), (Siqueira et al., 2004). Tube corrosion is related to the presence of chemically aggressive trace elements and compounds in the transported materials, usually attributed to presence of sulfur or halogens. A sketch of the two occasionally simultaneously appearing processes is illustrated in Fig. 1, where the corrosion related shrinking of wall thickness is related to the growing fouling layer.

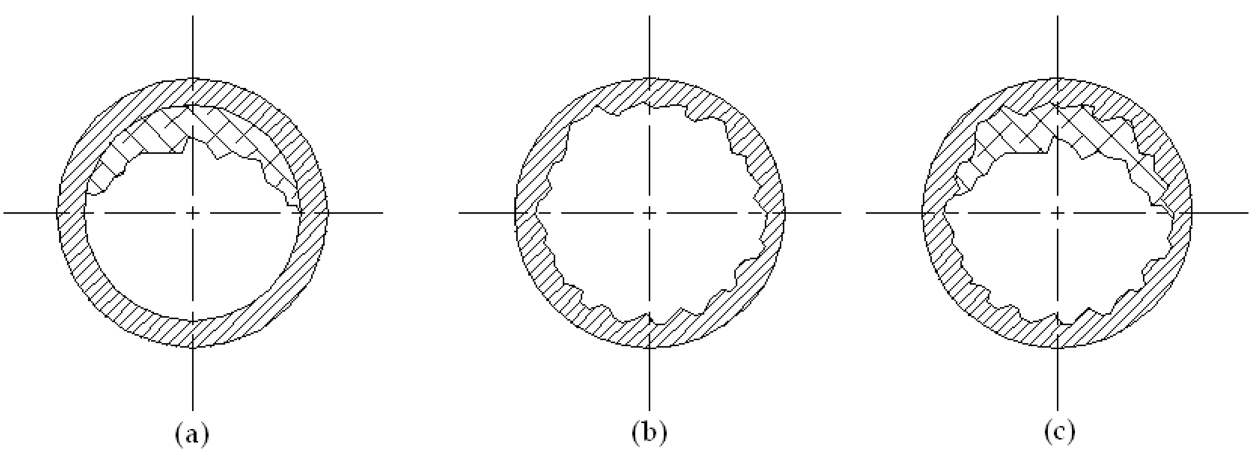

Figure 1. Cross-section view of tube aging processes: inhomogeneous fouling layer (a), corrosion (b), corrosion and fouling (c)

An example of tube fouling, observed in a selected duct section of an oil refining plant, is presented in Fig. 2. This duct is under test at the LIEC (Electronic Instrumentation and Control Laboratory) of Federal University of Campina Grande (UFCG).

The deposition rate commonly is very low, and it may take several months until critical thickness values are reached. Fouling in chemical plant duct systems and pipelines accounts for severe problems in plant operation as: reduction of the internal diameter of the tube; reduction of mechanical integrity and strength, reduction of plant operation lifetime, increase of the applied pressure to maintain flow through-put, crack formation and possibly catastrophic break-up. The associated increase of the energy consumption also comes along with higher operation and maintenance costs.

Figure 2. Photography showing the fouling layer formed in a duct section that transports crude oil (Petrobras-BR)

Duct systems and pipelines thus require regular and periodic inspection. Several methods have been proposed for early fouling detection in ducts, based on mass flow reduction (Krisher, 2003), electric resistance (Panchal, 1997) and ultrasonic techniques (Silva et al., 2005), (Lohr & Rose, 2002).

The key idea of the mass flow reduction technique is to monitor the corrosion process of a plate, made of the same material as the ducts. Such plate is put inside the pipe to obtain information regarding the fouling process (Krisher, 2003). The second group of methods, named electric resistance sensor techniques, is based on the analysis of the sensor resistance value to identify modifications in the pipe inner surface (Panchal, 1997). These two methods are intrusive, i.e. the elements for monitoring must be put inside the pipeline. This is a disadvantage, since plant operation should be interrupted for installation and analysis of the elements. On the other hand, the methods based on ultrasound are advantageous over those aforementioned methods, since those methods are not intrusive (Silva et al., 2005).

Guided acoustic waves are generated by the interference of Longitudinal (L) and Transverse (T) wave types: The longitudinal wave is generated when the movement of the particles is parallel to the wave propagation direction. The transverse wave is generated when the movement of the particles is perpendicular to the wave propagation direction. Guided waves are generated by the interference of these two wave types, when the thickness of the wall under test is smaller or equal than the wavelength of wave (Rose, 1995), (Lohr & Rose, 2002). Fig. 3 shows the formation of guided waves in a plate, when the thickness (*d*) of the plate is smaller or equal to the wavelength of wave (λ) (Silva et al., 2007).

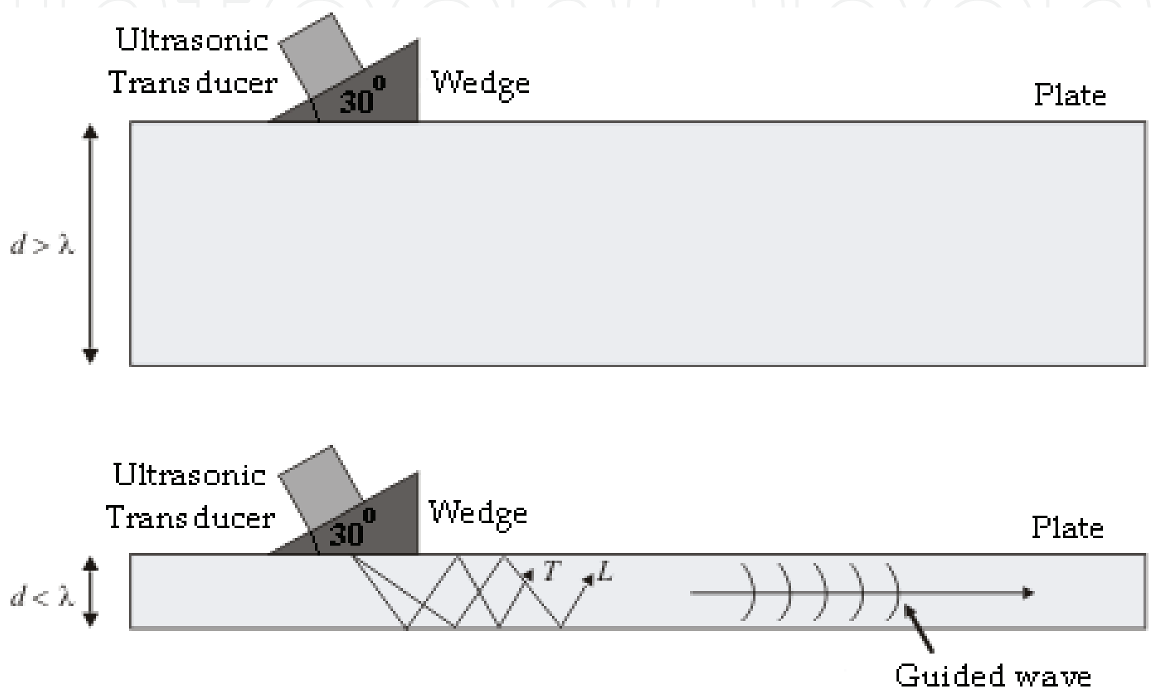

Figure 3. Representation of guided acoustic waves

Thus, to generate guided waves, two basic conditions are necessary: First, the pipe wall thickness under test should be smaller or equal than the wavelength of the spread signal, and this is possible adjusting the excitation frequency of the pulser; second, the angles of the used transducers must be chosen adequately. The angles of the transducers are determined by the shape of the wedge couplers that are made of acrylic. In the present case, it was observed that for angles larger than 40 deg the guided waves were not generated and the receiver didn't detect the transmitted signal (Silva, 2005). The transmitted waves were detected for wedge angles of 30 deg and 40 deg (commercial angular transducers are usually provided for 30 deg, 40 deg and 45 deg angles) (Silva, 2005).

Guided waves can travel up to 200 *m*, but there is a reduction in the amplitude of the signal due the attenuation in the medium and the distance (Rose, 1995). For the studied pipe, tests were accomplished with a distance variation among the transducers from 5 to 70 *cm* (size of the removable part of the pipe) and no amplitude reduction was observed, without fouling.

The ultrasonic transducers are typically excited with pulses and amplitudes that vary between 100 and 1000 *V*. The received signal can vary from microvolts to some volts. The received signal may exhibit frequency characteristics very different from the pulses used to excite the transmitter transducer, due the characteristics of the propagation media (Fortunko, 1991).

After recording at the receiver, the signals are amplified and filtered. The parameters like gain and bandwidth of the receiver are adjusted in agreement with the characteristics of the system under test. Choice of gain and bandwidth are also influenced by the used transducer, discontinuities and characteristics of the frequency response of the pulser. When the ultrasonic signal encounters a new interface (different material), the signal spreads also into this interface, and modifies the characteristics of the transmitted signal.
This chapter presents the use of a model for ultrasonic pulses, which spread through guided waves in a pipe, for fouling detection. The main goal is to estimate the parameters of the model and to observe the variations of these parameters with the presence of the fouling.
This chapter is organized in six sections: the first part is the introduction; section 2, the models and estimation method for ultrasonic pulses, in section 3 the proposed system, in section 4 the simulation results, experimental results in section 5 and concluding remarks are outlined in section 6.

2. Models and estimation for ultrasonic pulses

Some models of ultrasonic pulses are based on the diffraction scalar theory, while piezo-electric transducers were employed (Calmon et al, 2000).
When an ultrasonic pulse spreads through a layer of a medium of different material, the waveform of the pulse is modified, due to the attenuation and dispersion. In many media, a characteristic attenuation, which increases with frequency, has been observed. As result, the high frequency components of the pulse are more attenuated than the low frequency components. After crossing the layer, the transmitted pulse differs from the incident pulse, and it presents a different form (amplitude, frequency, phase) (He, 1998).
The patterns of ultrasonic pulses present important information regarding form, size and orientation of the reflections, as well as, the micro-structure of the propagation media of the pulses (Dermile & Saniie, 2001a), (Dermile & Saniie, 2001b).
Models of parametric signals are used to analyze ultrasonic pulses. These models are sensitive to the characteristics of the signal as bandwidth factor, return time, central frequency, amplitude and phase of the ultrasonic pulse. Some advantages have been discovered using signal modeling. First, estimates of parameters with high resolution can be found; second, the accuracy of the estimation can be evaluated; third, the analytical relationships between the parameters of the model and physical parameters of the system can be established. The ultrasonic pulses can be modeled in terms of Gaussian pulses, affected by noise. Each Gaussian pulse in the model is a non-linear function of the following parameters: bandwidth (α), return time (τ), central frequency (f_c), amplitude (β) and phase (φ). The estimation of these parameters can be obtained by non-linear parameter estimation techniques (Dermile & Saniie, 2001*a*), (Dermile & Saniie, 2001*b*).
Equation (1) is used by Dermile & Saniie (Dermile & Saniie, 2001*a*), (Dermile & Saniie, 2001*b*) to model the ultrasonic pulses.

$$S(\theta,t) = \beta e^{-\alpha(t-\tau)^2}\cos(2\pi fc(t-\tau)+\varphi) \tag{1}$$

Where θ = [α τ f_c β φ] represents the parameters to be estimated. The bandwidth determines the pulse time duration in the time domain, the return time is related with the location of the reflecting surface, the central frequency is governed by the frequency of the displacements

in the material. The pulse displays an amplitude and a phase, according to the impedance, size and orientation of the reflecting surface. This model is used for parameter estimation, in combination with tests that use the pulse-echo method, and a transducer that operates as both, a pulser and receiver.
Considering the effect of the noise in the estimation, a noise process can be included to the model (Dermile & Saniie, 2001*a*), (Dermile & Saniie, 2001*b*). Thus, the ultrasonic pulse can be modeled by equation (2):

$$x(t) = S(\theta, t) + e(t) \tag{2}$$

Where $S(\theta,t)$ denotes the model of the ultrasonic pulse and $e(t)$ denotes the additive white Gaussian noise.
This model can be extended to consider multiple ultrasonic pulses by equation (3):

$$y(t) = \sum_{m=1}^{M} S(\theta_m, t) + e(t) \tag{3}$$

Each parametric vector θ_m defines the form and location of the corresponding pulse completely. For computer programming purposes, the observation model expressed by equation (2) for an ultrasonic pulse can be written in the discrete form (Dermile & Saniie, 2001*a*), (Dermile & Saniie, 2001*b*), (Silva et al., 2007).
The Gaussian pulse model has been chosen as the algorithm for parameter estimation, since this model is more accurate and the parameters resemble the ultrasonic pulse in a more complete approach. The Gaussian pulse model is thus appropriate to determine the parameters of the guided waves method and the analysis of the fouling process is achieved by observing the variation of the estimated parameters.
The estimation problem relies on the determination of the parameters of the model, and modifications of these parameters in presence of fouling. Here, the non-linear estimation approach is employed, using programs developed with the MATLAB code (Hansenlman & Littlefield, 1996).

3. Proposed system

The proposed system for fouling monitoring using ultrasonic transducers is illustrated by the block diagram presented in Fig. 4. This system is composed by the ultrasonic pulser and receiver which are connected to the transducers and coupled to the pipe, in order to generate longitudinal guided waves.

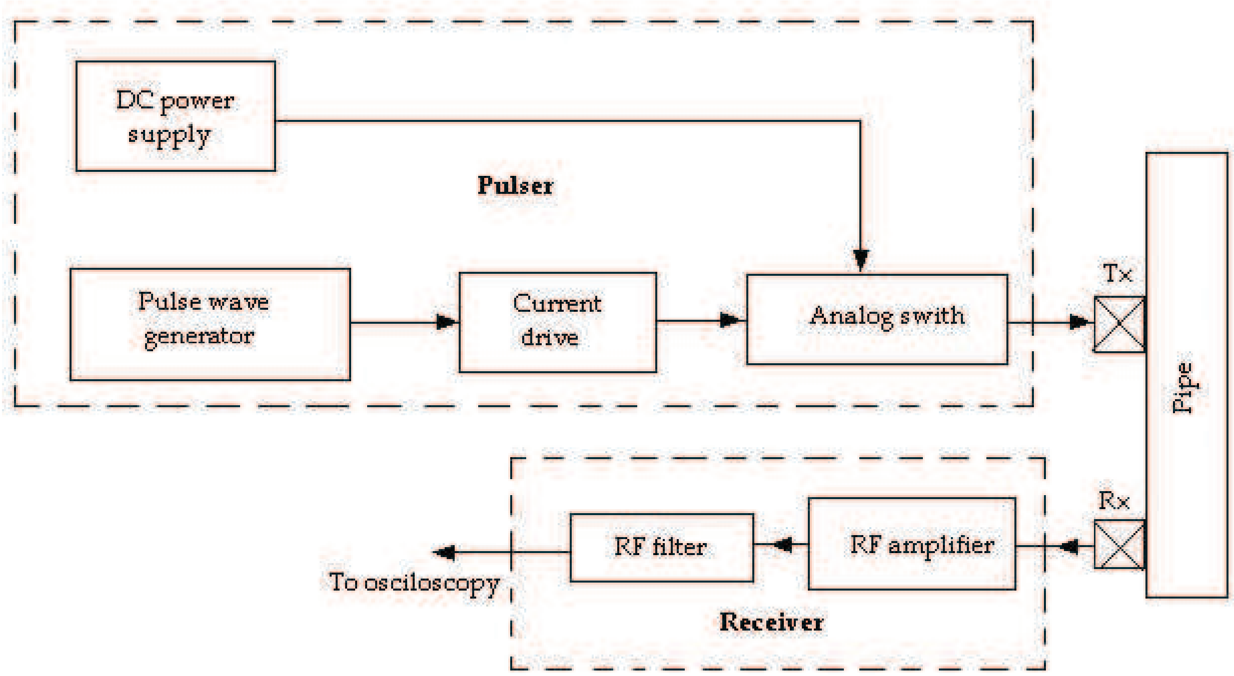

Figure 4. Block diagram of the proposed system with the pulser and receiver

The block diagram of the pulser circuit is shown in Fig. 5. The diagram comprises basically a DC power supply and a pulse wave generator, used to activate an analog switch, to obtain the pulses with the amplitude and frequency necessary to excite the ultrasonic transducer. A current drive is used to supply the current required by the analog switch.

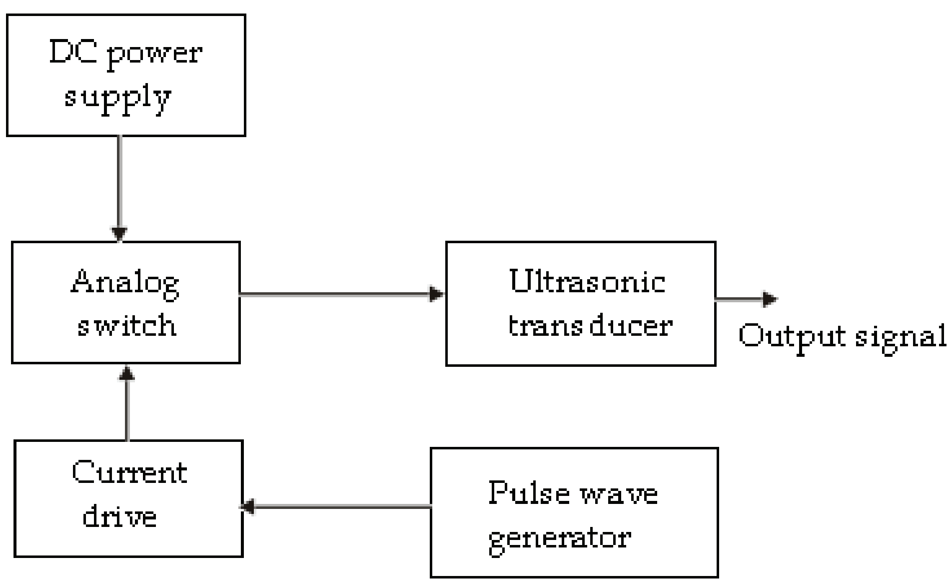

Figure 5. Block diagram of the pulser circuit

The waveform of the pulser output signal is shown in Fig. 6. This signal has 80 *V* maximum amplitude and 500 *kHz* frequency. These values are necessary for generation of the guided waves and monitoring at the receiver.

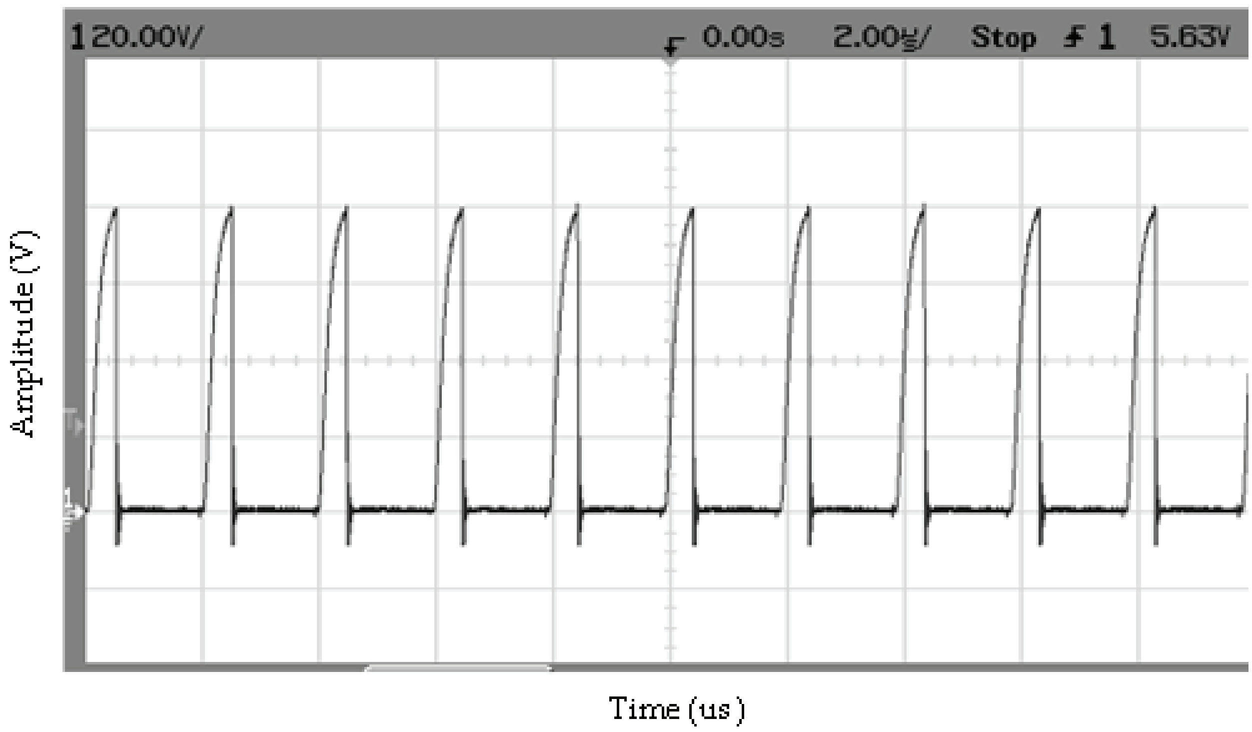

Figure 6. Waveform of the pulser output signal

The excitement signal of the pulser is a train of pulses with 80 *V* amplitude and 500 *kHz* frequency. This amplitude guarantees a minimum level of received signal (in the mV range), for smaller amplitude the received signal is too low to excite the receiver transducer. This frequency is necessary to guarantee the generation of the guided waves, once the propagation speed in the galvanized iron is known (4600 m/s) and the wavelength should be larger or equal than the pipe wall thickness (2.0 *mm*) (Silva et al., 2005).
A simplified block diagram of the receiver is presented in Fig. 7. In this diagram an initial amplification stage is used to increase the amplitude of the received signal, and a narrow band RF-filter to select the monitored signals.

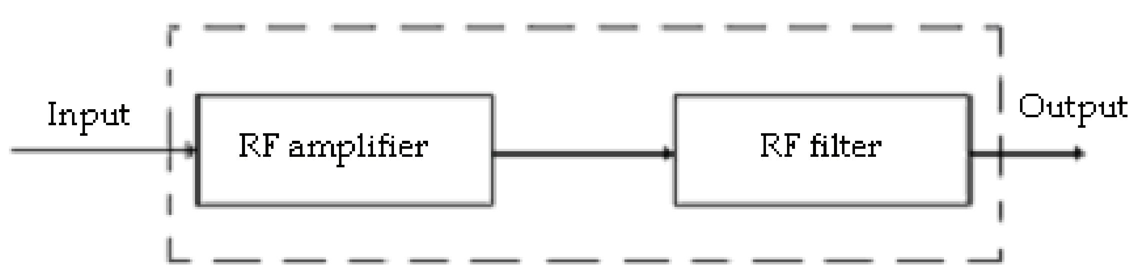

Figure 7. Simplified block diagram of the receiver

The receiver is designed, using amplification and filtering stages to detect the signals from the receiving transducer. The receiver circuit utilizes the integrated circuit AD8307, which is a logarithmic amplifier. Its output is a voltage value, proportional to the logarithm of the input signal amplitude, and its input impedance is equal to 50 Ω.

The waveform of the receiver output signal is presented in Fig. 8. This signal has 100 *mV* maximum amplitude and frequency in the *MHz* range, representing the typical feature of ultrasonic signals.

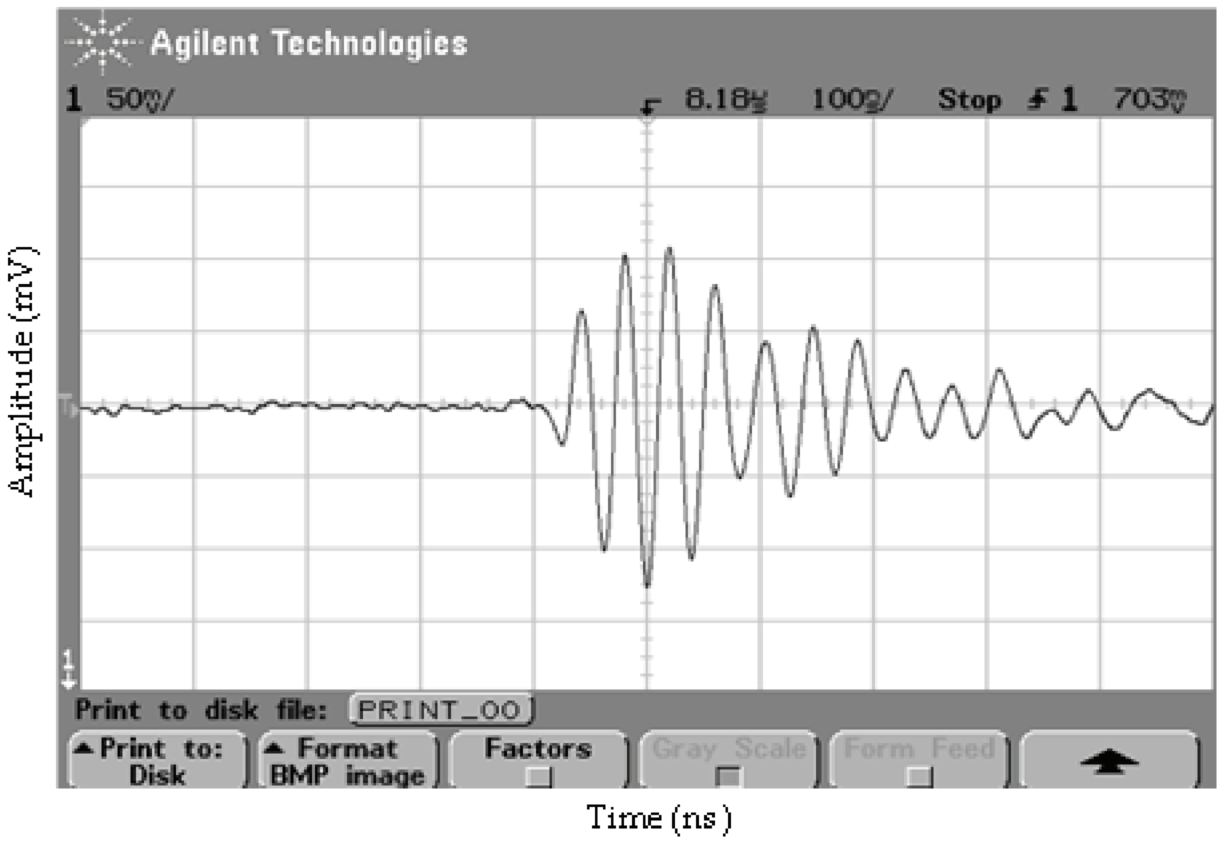

Figure 8. Waveform of the receiver output signal

The signals are monitored, using a digital oscilloscope. To detect the fouling layer, initially the amplitude reduction of the signals has been considered. However, towards an accurate analysis, other relevant features of the received signals are required as: frequency variations and phase. As mentioned before, the goal is to determine the parameters of a model for ultrasonic pulses and to analyze the variations of these parameters, under the effect of the fouling in the system. The fouling process was emulated by means of an experimental platform, in which the temperature, pressure and flow are monitored and controlled. Before each experiment, the tube was taken out of the experimental platform and the accelerated fouling layer deposition process inside the tube initiated. To speed up the fouling process, the same substances related to actual petroleum exploration were mixed with water and put into the pipe. The proportions of the substances deposited in the tube were subsequently increased. For 100 *l* of water, the following concentrations were used: 24.05 *g* of $Ca(OH)_2$; 9.9 *g* of $MgSO_4$; 2.472 *kg* of NaCl; and 16.99 *g* of $BaSO_4$. These proportions are the same, as found in the petroleum treatment factory of Petrobras in Guamare-RN-Brazil.

As outlined before, the model is used to determine the parameters using the method of the guided waves and the variation of the estimated parameters in the model of Gaussian pulses.

A diagram of the experimental platform for data acquisition is shown in Fig. 9. This platform was developed, in which the temperature, pressure and flow are monitored and controlled (Silva, 2005). The tubes were used as a medium to guide ultrasonic waves and periodically over several weeks measurements were performed to monitor the fouling process (Silva et al., 2007).

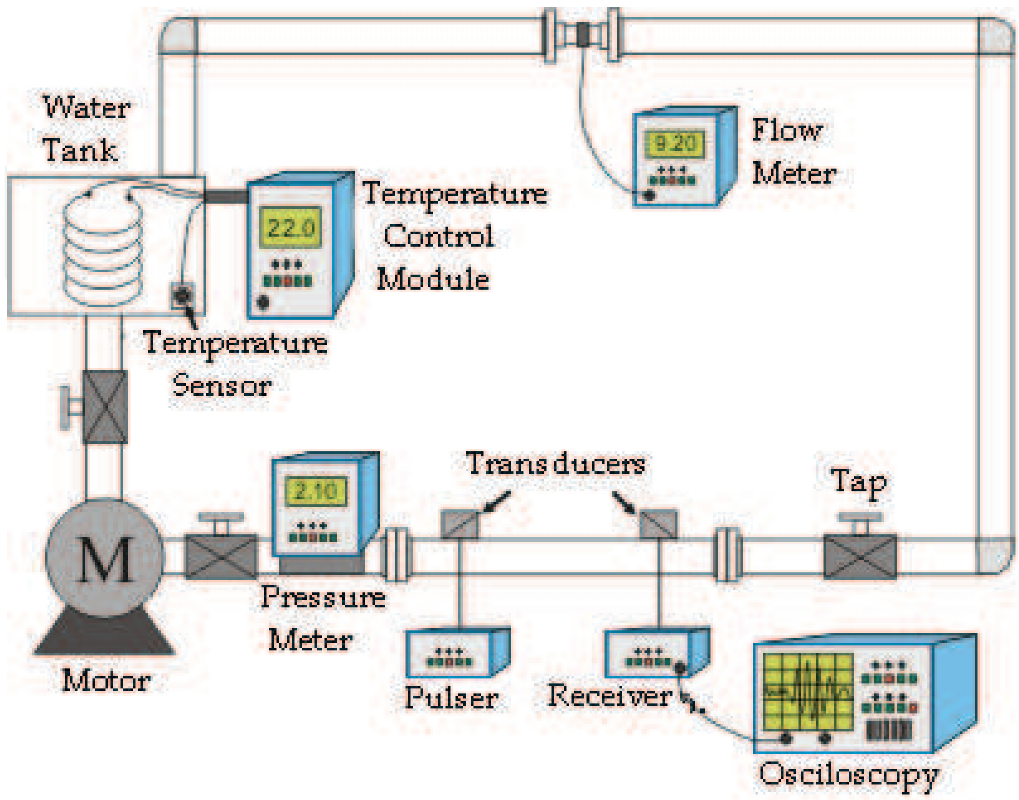

Figure 9. Diagram of the experimental platform

With the acquired data and using the models, the estimated parameters of the system have been used to analyze the behavior of the ultrasound signal and to observe the influence of the fouling. The non-linear estimation methods (least square non-linear) were used, with the software MATLAB, to determine the model parameters (Hansenlman & Littlefield, 1996).

4. Simulation results

A preliminary simulation study was accomplished by using the model for ultrasonic pulses provided in (1). The single pulse case was simulated and the parameter vector θ was estimated, using a program developed with MATLAB. In Table 1, the values obtained with the simulation for a single pulse are shown. The choice of θ_0, the initial parameter vector, is quite critical to obtain good results with relatively few iteration steps. The selection of the initial parameter relies on the characteristics of the observed signal.

	Real Parameters	Estimated Parameters
α	38.00	36.00
τ	0.70	0.50
f_c	18.00	16.00
β	0.80	0.70
φ	0.90	0.80

Table 1. Simulation results with single pulses

A signal with multiple pulses was also simulated with a program using MATLAB. In Table 2 are presented the values obtained with the simulation for multiple pulses.

	Real Parameters	Estimated Parameters
α_0	38.00	36.00
τ_0	0.70	0.50
f_{c0}	18.00	16.00
β_0	0.80	0.70
φ_0	0.90	0.80
α_1	38.00	36.00
τ_1	1.50	1.40
fc_1	16.00	14.00
β_1	0.60	0.50
φ_1	0.85	0.80

Table 2. Simulation results with multiple pulses

The results of simulation for the parameter estimation of a single pulse are presented in Fig. 10. The estimated parameters curve is quite similar with the real parameters curve. For this simulation the processing time is 4.42 *s*, the measurement error is 0.0099 (quadratic medium error) and the number of iterations is 20. The results of simulation for the parameter estimation of the signal with multiple pulses are presented in Fig. 11; this simulation also provides an excellent result in relation to the estimated parameters. For this simulation the processing time is 215.37 *s*, the measurement error is 0.0331 and the number of iterations is 40 (Silva et al., 2007).

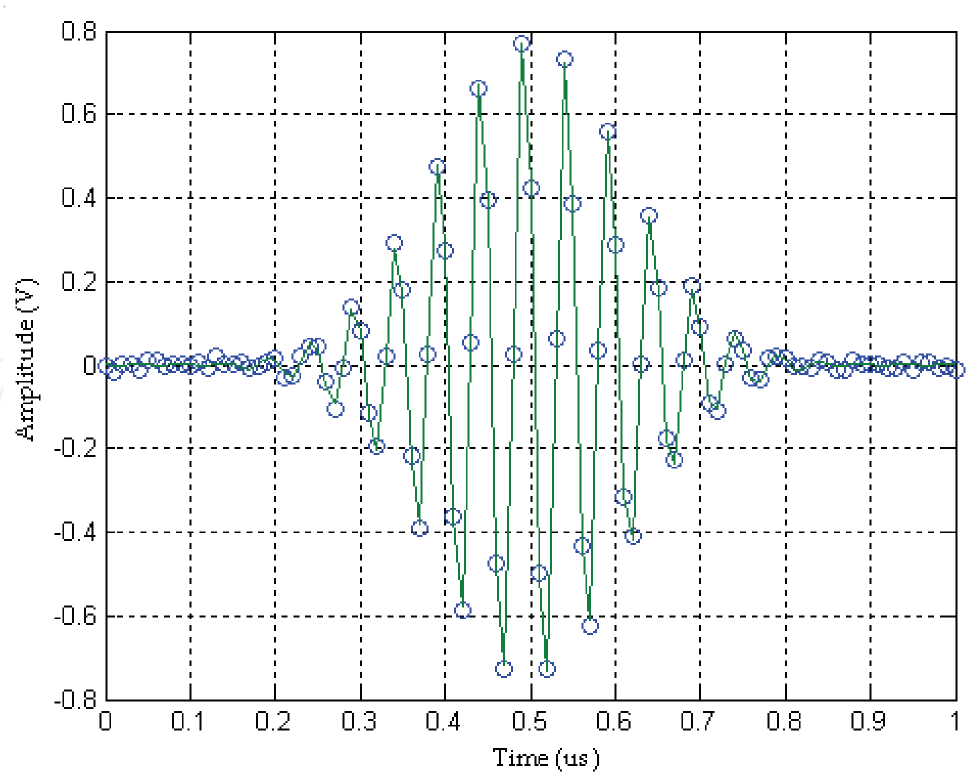

Figure 10. Results of the simulation for a single pulse: The points represent the real signal and the full line represents the estimated signal

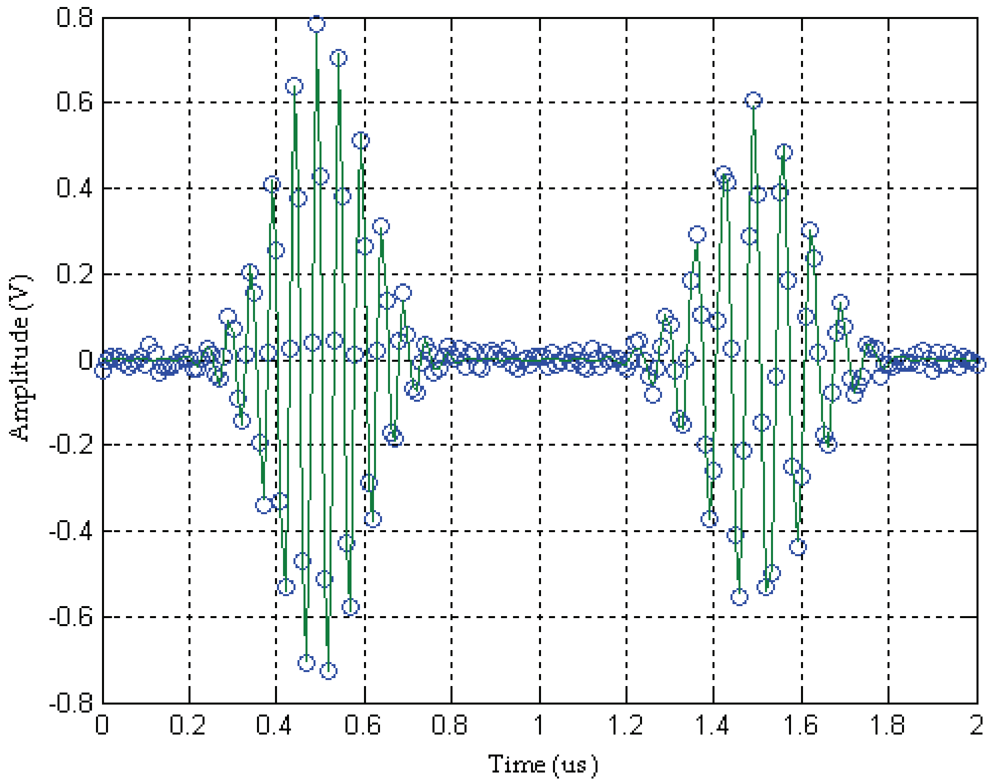

Figure 11. Results of the simulation for a multiple pulse: The points represent the real signal and the full line represents the estimated signal

As the number of ultrasonic pulses increases, the dimension of the parameter vector increases and, consequently the number of iteration steps also increases. To reduce the number of parameters to be estimated, we have employed spectral analysis (FFT) to determine what frequencies are present in the signal detected with multiple pulses, using MATLAB. The results of the simulation of a signal with multiple pulses and the FFT of this signal are presented in the Figs. 12 and 13 respectively. It was considered as parameters for the real signal: $\alpha_0 = 38$, $\tau_0 = 0.5$, $f_{c0} = 20$, $\beta_0 = 0.8$, $\varphi_0 = 1$; and $\alpha_1 = 28$, $\tau_1 = 1.0$, $f_{c1} = 15$, $\beta_1 = 0.6$, $\varphi_1 = 0.80$; and $\alpha_2 = 14$, $\tau_2 = 1.5$, $f_{c2} = 10$, $\beta_2 = 0.9$, $\varphi_2 = 0.90$. Using the FFT, the present frequencies in the signal can be determined accurately, thus reducing the number of parameters to be estimated. Fig. 13 shows the three present frequencies in the signal of the Fig. 12 (Silva et al., 2007).

With these simulations, it is possible to observe the behavior of the Gaussian pulses and to analyze the estimated parameters for these pulses, as well as to test the quality of the developed programs and to evaluate its performance. An important result in relation to the estimation procedure is the choice of the initial parameters, which is obtained from an observation of the measured signals. A bad choice increases the processing time substantially, and the estimation error.

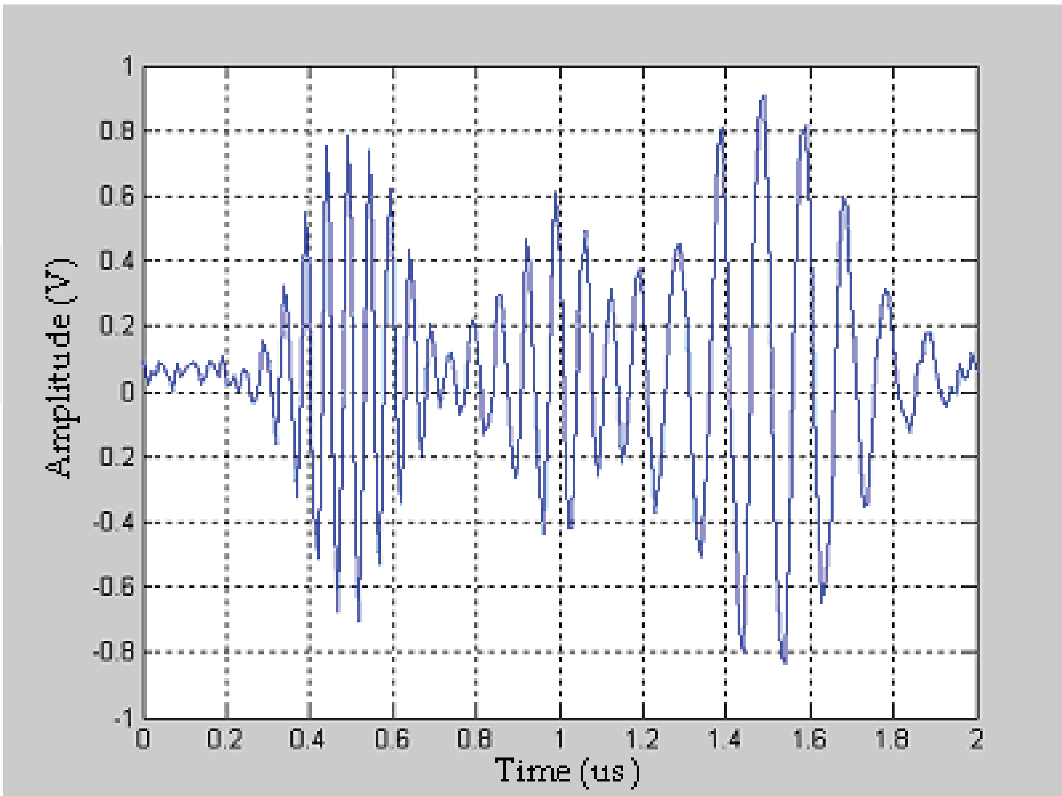

Figure 12. Representation of a signal with multiple pulses

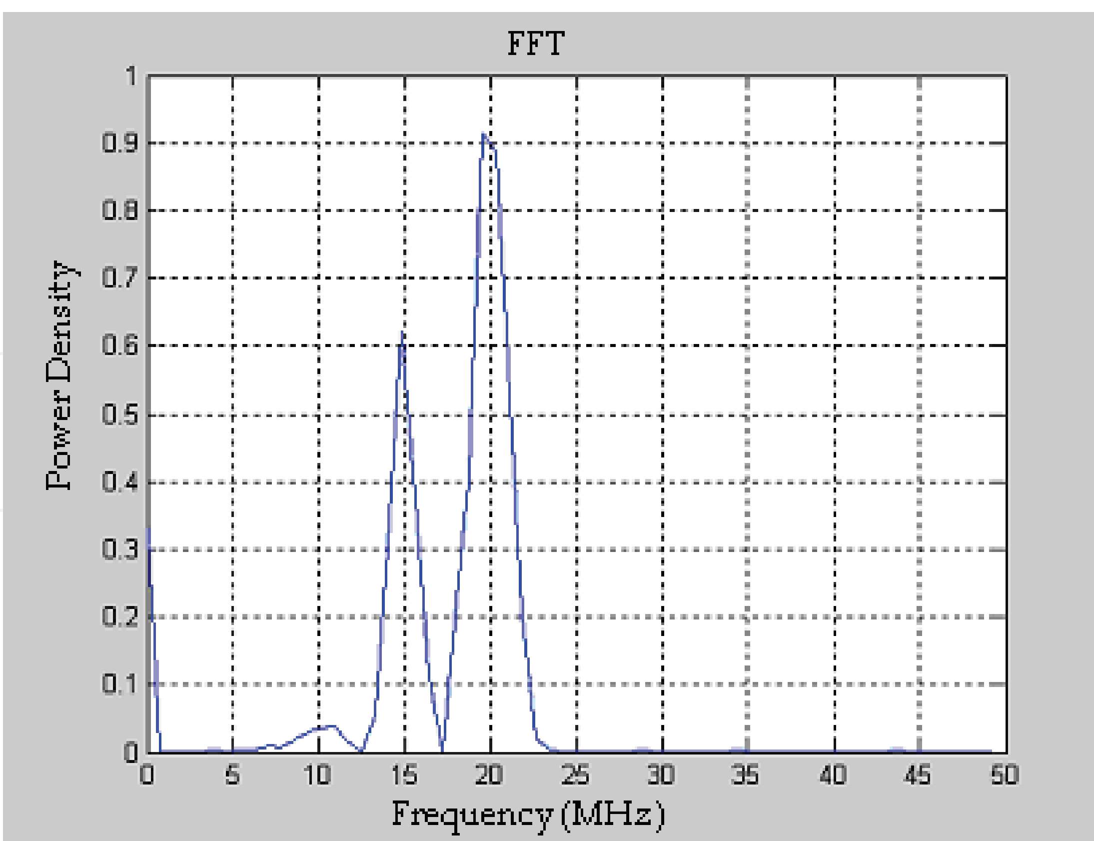

Figure 13. Representation of FFT for the signal of the Fig. 12.

5. Experimental results

A calibration step to define the pipeline signature is initially carried out and the pipe is completely cleaned, ensuring absence of a fouling layer. The inclination angle of the used transducers is 30^0. The maximum frequency of operation is 2 *MHz*, the transmitter is excited with pulses of 80 *V* and the sampling frequency is 100 *MHz*. The received signal is monitored, and the characteristics of these signals (amplitude, frequency, etc) are taken as reference for fouling detection.

The new results presented in this section were obtained with the same methodology presented in Silva (Silva et al., 2007).

In the experimental platform, it was possible to acquire the data in the receiver output by means of a digital oscilloscope. The obtained ultrasonic signals are illustrated in Figs. 14, 15 and 16, respectively. The signal shown in Fig. 14 represents the pipe signature, i.e., the pipe without fouling. The signal shown in Fig. 15 presents the pipe with 1 *mm* of fouling and Fig. 16 depicts an ultrasonic signal related to a pipe exhibiting a 3 *mm* fouling layer.

For the signal of Fig. 14, the processing time is 145.35 *s*, the measurement error is 2.65 (quadratic medium error) and the number of iterations is 8. For the signal of the Fig. 15 the processing time is 38.30 *s*, the measurement error is 1.25 and the number of iterations is 6. And for the signal of the Fig. 16 the processing time is 34.25 *s*, the measurement error is 1.15 and the number of iterations is 4.

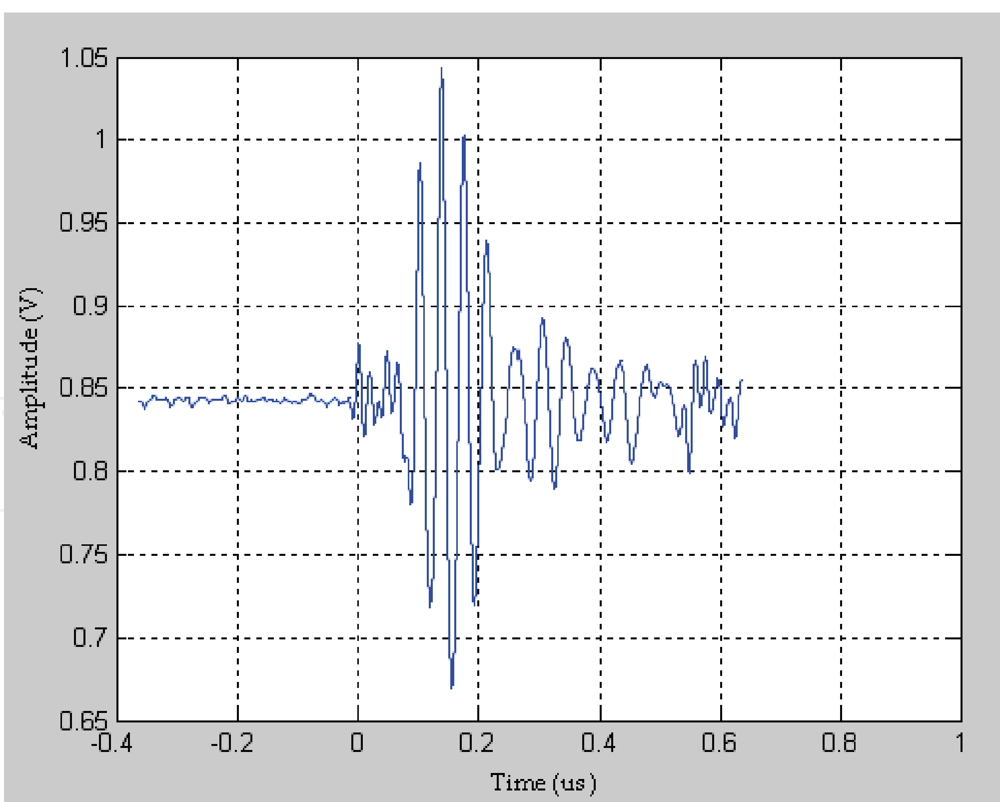

Figure 14. Representation of the receiver output signal without fouling using MATLAB

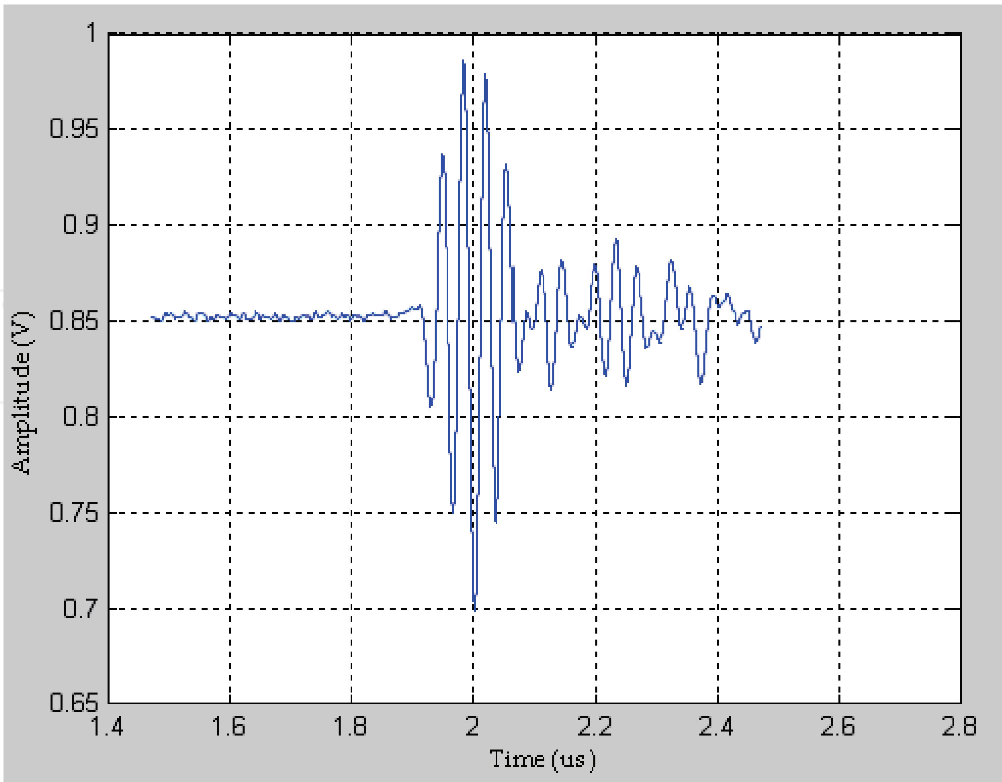

Figure 15. Representation of the receiver output signal with 1 *mm* of fouling using MATLAB

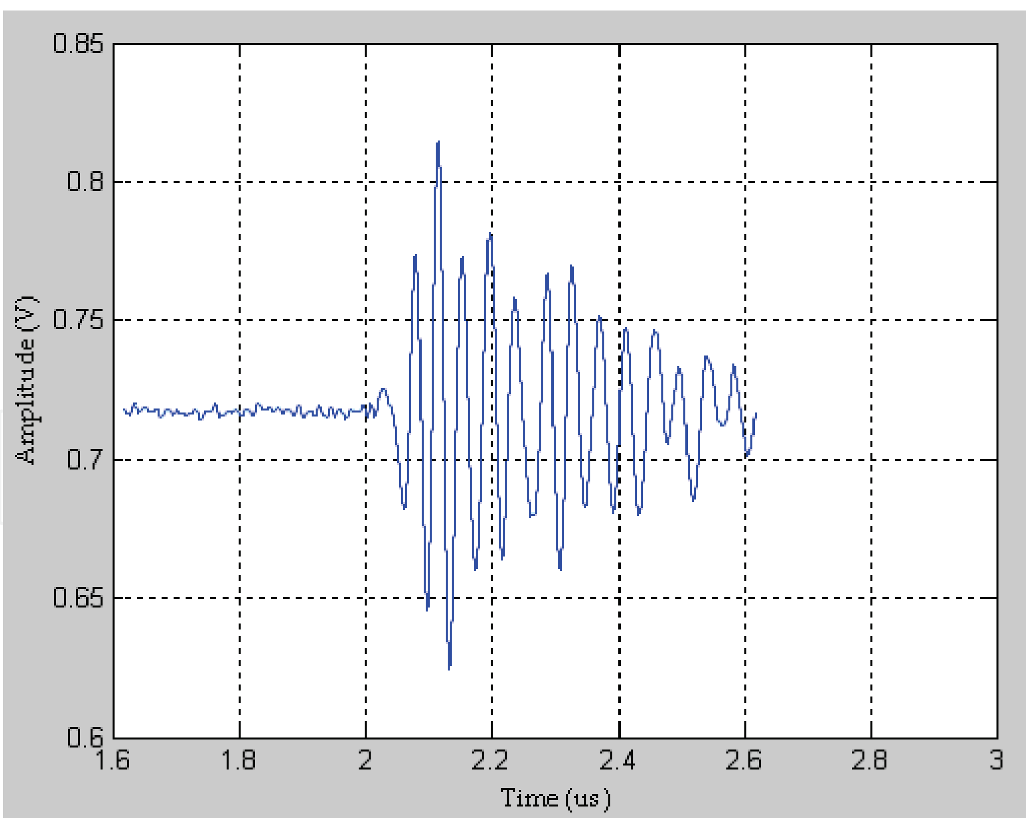

Figure 16. Representation of the receiver output signal with 3 *mm* of fouling using MATLAB

From the analysis of the ultrasonic signal, it was found that the amplitude reduction provides important information regarding the fouling process. This effect occurs, since the fouling layer modifies the propagation medium of the ultrasonic signals, thus providing a second leakage path in the received signal.

A further program, developed with MATLAB was used to determine the spectral features and frequencies in the measured signals in the time domain from Figs. 14, 15 and 16 respectively. The signals obtained with the FFT are represented in Figs. 17, 18 and 19 respectively. For the first signal, the determined frequency is 29 *MHz*, for the second signal (with 1 *mm* of fouling) the determined frequency is 27 *MHz* and for the third signal (with 3 *mm* of fouling) the determined frequency is 24 *MHz*. The estimated parameters for the frequency of the three signals represent a good approximation in relation to the measured real signal.

With the use of FFT, it was possible to determine the frequencies that are present in the ultrasonic signals. Since the frequencies of the pulses are not needed of being estimated and the number of parameters is reduced, the estimation times and the iteration numbers are also reduced.

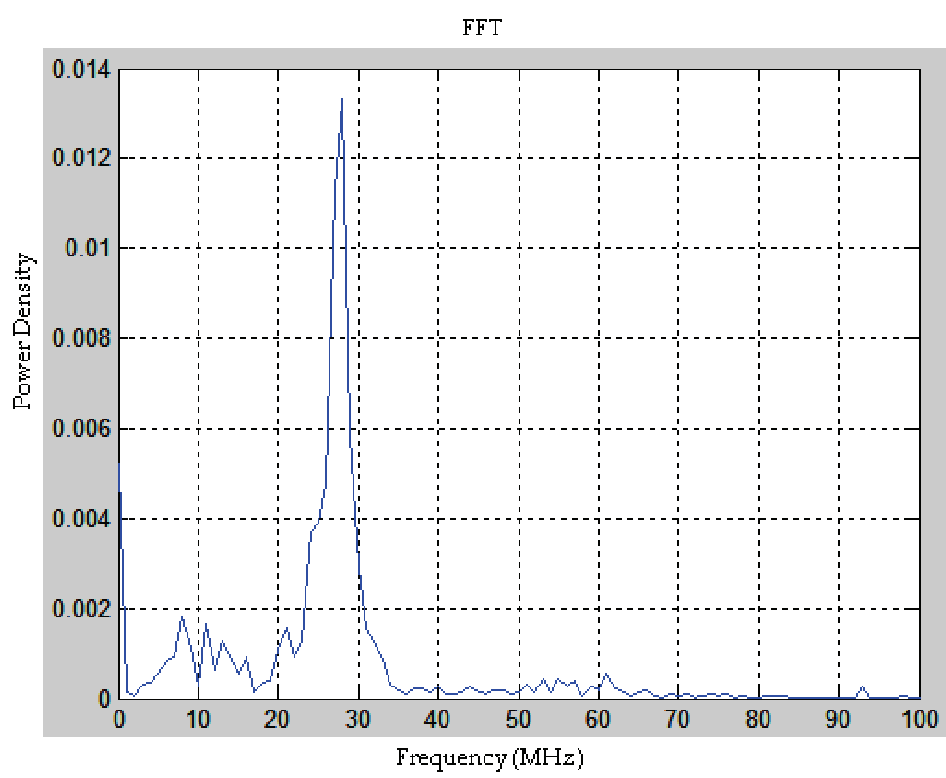

Figure 17. Representation of FFT for the measured signal without fouling

With the model for Gaussian pulses and using a program developed in MATLAB, it was possible to identify the parameters for the measured signal that are represented in Figs. 14, 15 and 16. The results with the parameter estimation for these signals are illustrated in Figs. 20, 21 and 22 respectively, and we can observe that the parameter modifications are due the fouling process in tubes.

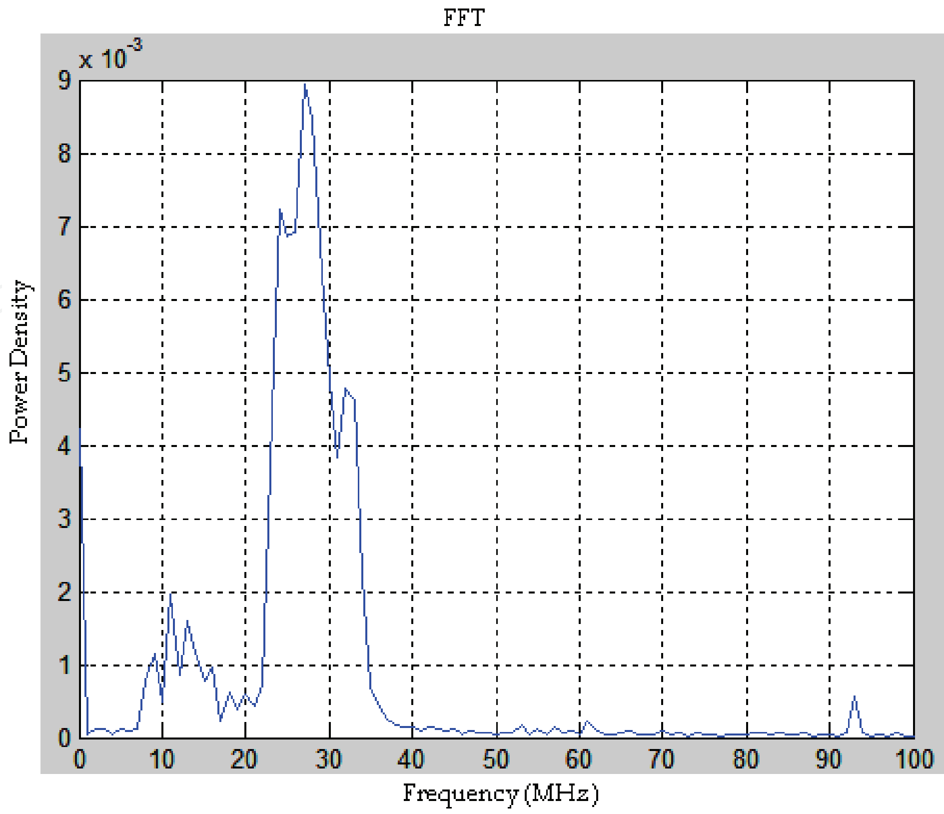

Figure 18. Representation of FFT for the measured signal with 1 *mm* of fouling

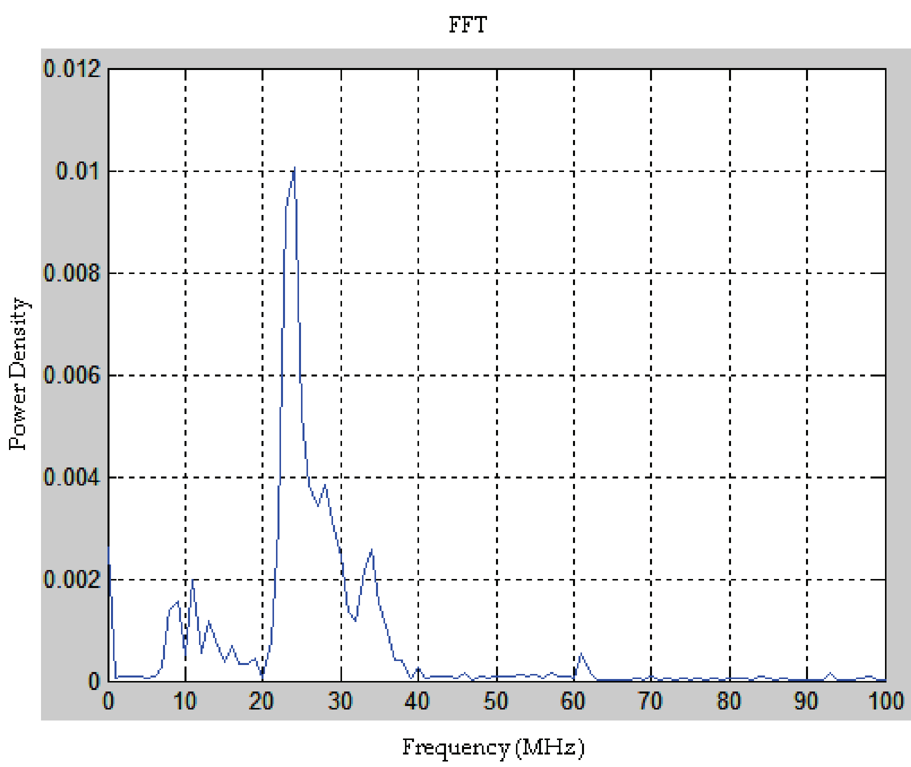

Figure 19. Representation of FFT for the measured signal with 3 *mm* of fouling

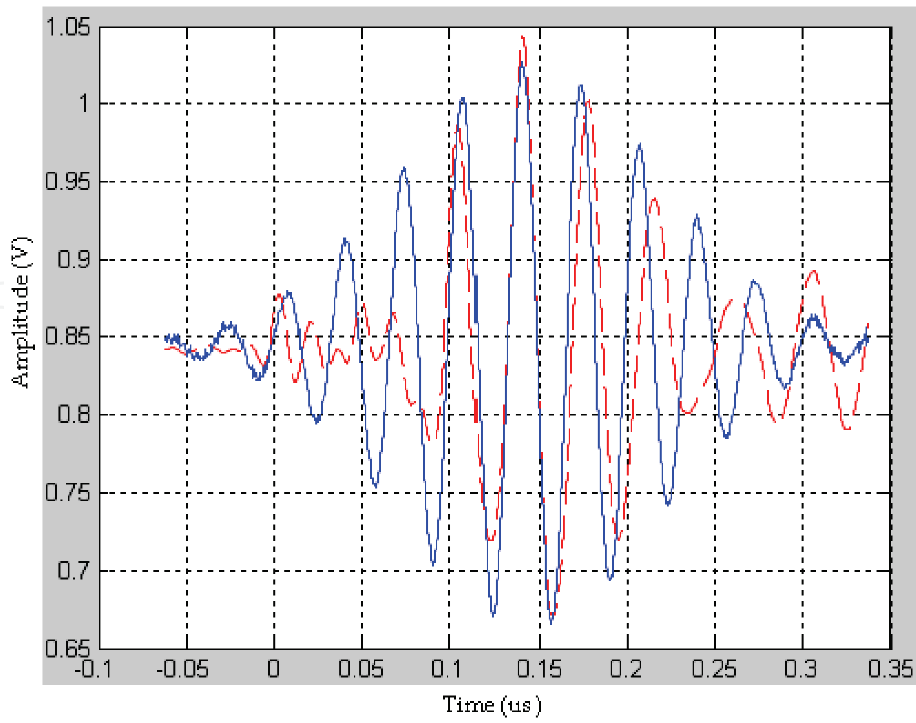

Figure 20. Representation of the measured signal (dashed signal) and of the estimated (continuous signal) without fouling

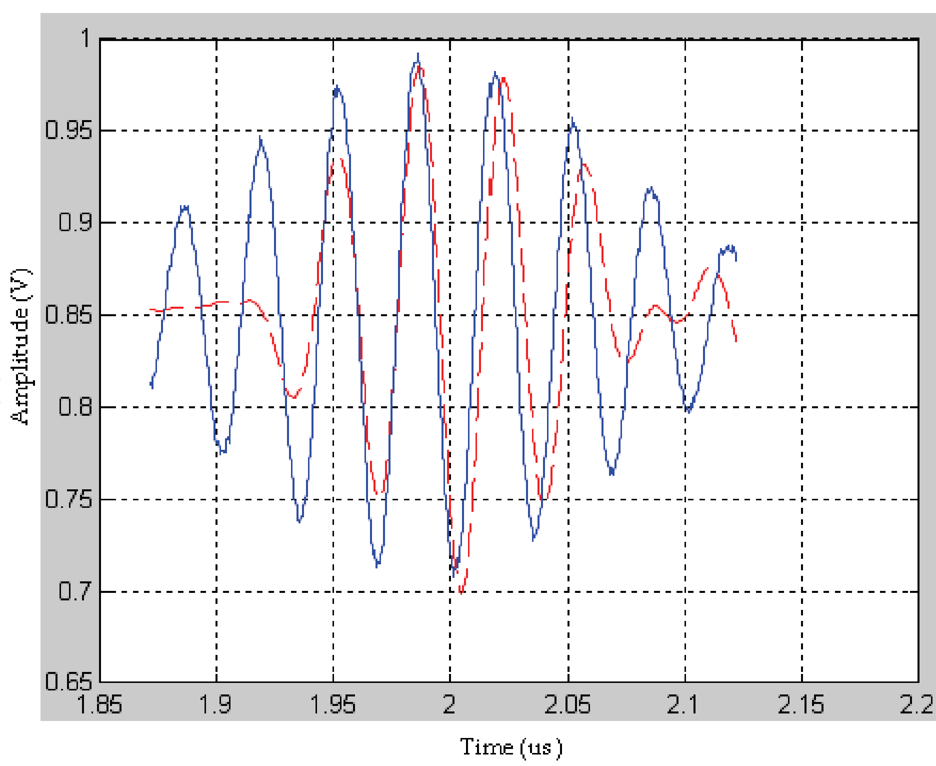

Figure 21. Representation of the measured signal (dashed signal) and of the estimated (continuous signal) with 1 *mm* of fouling

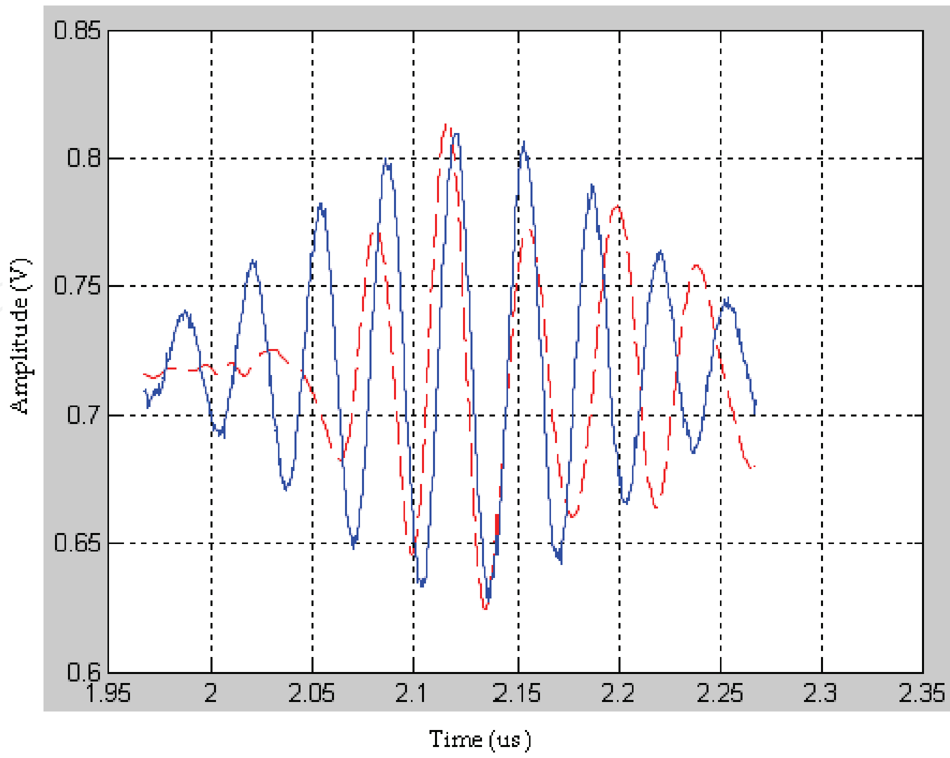

Figure 22. Representation of the measured signal (dashed signal) and of the estimated (continuous signal) with 3 *mm* of fouling

The estimated parameters for the signals are presented in the Table 3.

	Signal without fouling	**Signal with 1 *mm* of fouling**	**Signal with 3 *mm* of fouling**
α	85.0	80.0	75.0
τ	0.16	1.95	2.10
f_c	30.0	27.0	24.0
β	0.18	0.14	0.09
φ	0.80	0.85	0.90

Table 3. Estimated parameter values for the measured signal

Analyzing the data in Table 3, we observe that the parameters bandwidth (α), central frequency (f_c) and amplitude (β) decrease with the increase of the fouling layer, while the parameters return time (τ) and phase (φ) increase.

The presented models are considered as a good approach to resemble recorded real signals. Parameter variations resulting from the presence of tube fouling are well resolved. The absolute values of the signals are compared and modifications, as increase or reduction, of the absolute parameter values are easily observable.

6. Concluding remarks

In this chapter, a signal analysis method of ultrasonic signals has been presented and this method utilizes a parameter estimation algorithm for fouling detection. The model is based on Gaussian pulses, therefore this model is more complete and the parameter estimation provides higher accuracy. Results were obtained with simulations and with acquired experimental data. For treating of a non-linear system, this problem cannot be solved using optimization algorithms as efficient as the least square method.

Thus, programs were developed with MATLAB for estimation of non-linear systems. With the use of the Fast Fourier Transform (FFT) algorithm the spectral features i.e. frequencies present in the ultrasonic signals were resolved. Since the number of parameters is lowered, also the estimation time and number of required iterations are reduced.

With this approach presence of fouling layers can be easily detected, taking as reference the estimated parameters of the clean, fouling free tube section. Systematic variations of these parameters originate from inner tube fouling deposits. Different points of the pipe have been evaluated to identify their exact positions.

It is anticipated in future investigations to extend the analysis and include the attenuation rate of the received signal amplitude, in accordance with the amount of substance deposited onto the inner tube surface, and to verify the variation of the oscillations as a function of the substance type deposited inside the pipeline. In addition, it is also desired to evaluate other methods with ultrasonic waves, such as the circumferential guided wave method.

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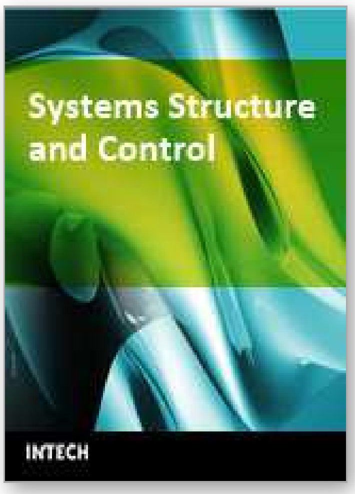

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