AN ACOUSTIC INSPECTION METHOD FOR DETECTING PRE-EXISTING LEAKS IN LIQUID TRANSPORTATION PIPELINES

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Abstract. *The main objective of this paper is to present a new leak detection technique based on active acoustic inspection of the pipeline, which is capable of detecting pre-existing leaks in liquid transportation pipelines. The acoustic pulses generated experimentally, were processing through software developed in LabView based on genetic algorithm (GA), which fitted a parameterized pulse model to measured ones. The experimental tests were executed at the pilot pipeline of the Industrial Multiphase Flow Laboratory at University of São Paulo in the campus of São Carlos – SP. Results confirm that the behavior of these parameters, particulary of the attenuation and frequency modulation ones, are indicative of the leak existence and position and, thus, can be used in an on-line LDS system.*

Keywords*: leak detection, acoustic propagation, hydraulic transient, signal processing*

1. INTRODUCTION

The transportation of petrochemical products through pipelines is the most common option, both in industrial applications involving long distances as well as in distribution networks in which a product must be delivered to a number of processes or customers. Due to safety and environmental reasons, the operation of such pipelines must include an on-line Leak Detection System (LDS) which promptly detects and assesses the occurrence of a leak, particularly if the transported product is toxic or inflammable. This need is absolutely clear in view of the significant number of accidents that have been happening, usually with important economical and environmental consequences. The techniques currently applied cover a large variety of methods, going from visual inspection to sophisticated hardware/software based specialist systems. Focusing on LDS's requiring on-line instrumentation installed at the ends of the pipeline, or, at least, at a few locations kilometers apart, these techniques can be grouped into two categories: 1) fast signal processing based methods and 2) slow process signal based methods.

"Among the fast signal processing techniques, probably the most applied method rely on detecting the presence of pressure waves associated with the flow transient (acoustic) caused by the appearance of the leak, Silk and Carter (1995)". Generally speaking, acoustic LDS's are applicable to liquid, gas and some multiphase pipelines, they are fast and locate the leak accurately, but the precision of the estimated leak flow rate is poor. Another important characteristic is that an acoustic LDS is not suited for detecting gradually developing leaks (progressive).

The basic motivation of this paper is present a new leak detection technique, based on active acoustic inspection of the pipeline suited for detecting pre-existing leaks in liquid transportation pipeline.

According to the literature, several techniques for leak detection based on transient flow, have been presented as "Mpesha (2002) that proposed a method for leak detection that uses the frequency response obtained through a non-periodic excitation", "Lee et al. (2006) presented an experimental validation of the frequency response method, producing transient signals by a side-discharge solenoid valve" and "Sattar (2008) proposed the use of frequency response for leak detection in which based on the variation of the amplitude of pressure oscillations at the even harmonics", but all the techniques described here have limitations due to their no applicability for real pipelines in which noise and strong nonlinearities play a major role.

2. THE LEAK DETECTION AND ASSESSMENT PROBLEM

This paper presents a new leak detection technique, based on active acoustic inspection of the pipeline, suited for detecting pre-existing leaks in liquid transportation pipeline. More precisely, acoustic pulses are artificially produced and injected in the flow at one end of the monitoring pipeline section and travels to the other end where an acoustic pressure sensor is placed in order to measure the corresponding signal. During the travel of these pulses from one end to the other end of the pipeline, attenuation and deformation result from the flow characteristics and pipe geometry. If a leak exists somewhere in the acoustic path, the measured pulse will by different from the one measured prior to the existence of the leak .The figure Fig. 1 shows the comparison of two of such pressure pulses, propagating without and with a leakage. In other words, a leak can be detected by assessing attenuation and deformation and comparing the corresponding parameters with reference previously determined ones without leak.

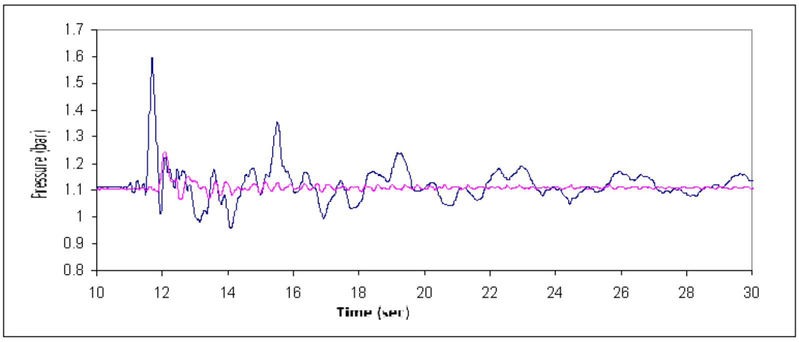

Figure 1. Comparison of two pressure pulses, propagating without and with a leakage.

The proposed acoustic inspection method based on the analysis of pulses through a signal processing software which fitted a parameterized pulse model to the measured ones. The parameters used in the model are amplitude, central frequency, delay, frequency modulation exponent and attenuation coefficient. This software is based on genetic algorithms, which will be described in more details in the sequel.

3. LEAK DETECTION BASED ON ACOUSTIC SENSING

“The sudden structural failure of a transport pipeline originates a leak that, by its turn, engenders a hydrodynamic transient that propagates at the speed of sound up and downstream along the pipeline. This transient is characterized by pressure and velocity oscillations reflecting the evolution to a new dynamic equilibrium between pressure (elastic) and inertia energy modes. Thus, detecting the rupture of the pipeline becomes a problem of detecting a specific waveform embedded in pressure, velocity or any other monitoring signal. This is a very well defined problem in signal analysis and there are several methods that can be applied, depending on the specificities of the problem. “Usual approaches are simple correlative filters Allen and Mils (2004)” or, more recently, “the so-called neural filters Szirtes et al. (2005)” which have the property of autonomously learning new waveforms. For instance, if P_{in} (t) is the pressure signal measured at the inlet end of the pipeline, and if δ (t) is the waveform associated to the leak, the following correlation signal $r(t)$ is defined:

$$r(t) = \frac{1}{\int_{t-T}^{t} \delta(\tau)^2 \, d\tau \cdot \int_{t-T}^{t} P_{in}(\tau)^2 \, d\tau} \left[\int_{t-T}^{t} P_{in}(\tau - t) \cdot \delta(\tau) \, d\tau \right]^4 \tag{1}$$

in which T denotes the temporal support of the sought waveform. It is evident that $0 \leq r(t) \leq 1$ and $r(t) = 1$ only if $P_{in}(t)$ matches $\delta(t)$ locally. An alarm is then triggered if the correlation signal exceeds a predefined convenient threshold. The following figure Fig. 2 shows pressure signals measured at both ends of a 2 km oil pipeline during a simulated leak test.

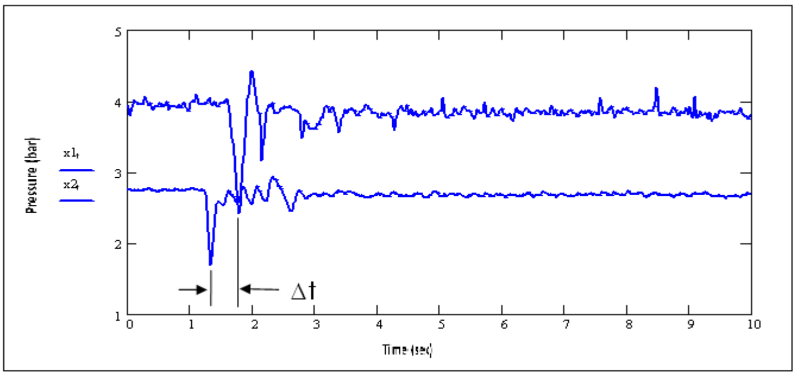

Figure 2. Characteristic pressure waveforms during a simulated leak test.

Once these pulses are detected at both ends of the pipeline, the delay ΔT between them is used to determine the leak location ℓ , according to the equation:

$$\Delta T = \int_0^{\ell} \frac{dx}{U(x)-a(x)} - \int_{\ell}^{L} \frac{dx}{U(x)+a(x)} \tag{2}$$

It is clear that to solve Eq. 2 it is necessary to supply the average flow velocity and the acoustic propagation speed profiles, which are dependent on the local temperature and pressure. A simplified version of this equation can be solved by assuming average constant values for a(x) and U(x). After integration the leak location results: Seleghim and Martins (2008)".

$$\ell = \left(\Delta T - \frac{L}{\bar{a}+\bar{U}}\right)\cdot\left(\frac{\bar{a}^2+\bar{U}^2}{2\cdot\bar{a}}\right) \tag{3}$$

where $\bar{a}$ is the average acoustic velocity and $\bar{U}$ is the average flow velocity .

4. GENETIC ALGORITHMS

"A Genetic Algorithm (GA) is a stochastic search algorithm based on the concepts of evolutionary theory, Holland (1975), Goldberg (1989)". More specifically, solution candidates of the optimization problem (individuals) compete among themselves for the opportunity of transmitting their characteristics to new generations of solution candidates generated from the old ones (reproduction). The best fitted individuals have better chances of reproducing, i.e. those for which the optimization function evaluates to more optimized values are more likely to reproduce (selection), so that good characteristics tend to be preserved in new generations (elitism). Reproduction is also affected by random changes occurring at a certain probability (mutation), which enables the emergence of new characteristics, not initially present in the parent generations, and their exploration through the survival or decline of the mutant individuals. The application of these concepts into a particular optimization problem requires a special formalism which will be described for the problem treated in this paper.

The error function is defined as the norm of the difference between a prospective or model pulse $\Psi_{mod}(t)$ and the actual acoustic pulse $\Psi_{actual}(t)$ obtained from data acquisition:

$$e(a_0,\Omega,t_{0,}\beta,\alpha) = \int_{\varepsilon} \left[\psi_{\text{mod}}(t) - \psi_{actual}(t)\right]^2 dt \tag{4}$$

where ε is a convenient integration interval and ($a_0, \Omega, t_0, \beta, \alpha$) define the model pulse such as

$$\psi_{\text{mod}(t)} = a_0 \sin(2\pi\Omega(t-t_0)^{\beta} \exp(-\alpha(t-t_0)) \tag{5}$$

where a_0 is amplitude, Ω central frequency, t_0 delay, β is the frequency modulation exponent and α is the attenuation coefficient. This error function is shown as the Fig.3, in which show the model pulse and the actual acoustic pulse have been compared.

Thus, Eq. 5 will be the fitness of the candidate solution given by ($a_0, \Omega, t_0, \beta, \alpha$). One particular generation is defined as a collection of Npop individuals such as

$$C_i = (a_0,\Omega,t_0,\beta,\alpha)_i\,,\ for\, i = 1,2....\ Npop \tag{6}$$

which will reproduce to form succeeding generations according to the corresponding values of the fitness function so that the best fit ones have better chances of reproducing. The reproduction process is accomplished by combining the genes of two or more parent individuals. This can be done by "merging randomly defined genes segments (geometric crossover): Radicliffe (1990), Spears and De Jong (1991)" or by "summing them up according to specific weights (arithmetic crossover): Davis (1991), Gen and Cheng (1997), Mühlenbein and Schlierkamp-Voosen (1993)". In this paper we adopted the so called arithmetic reproduction strategy, here defined as

$$C_{son} = \mu C_{mother} + (1-\mu) C_{father} \tag{7}$$

where μ is a random number varying between [0 , 1], C_{mother} is the best fit individual (smallest error) and C_{father} is the second best fit individual.

The reproduction scheme produces a steady convergence to the optimal solution but suffers from some drawbacks as, for instance, premature convergence, trapping by local minima or the dramatic convergence decrease due to plateaus in the optimization hyper-surface. To avoid this, from time to time, at a given probability, some of the reproduction rules are intentionally broken in a way that the generated descendents may acquire new features not necessarily present in the preceding generation. This process, called mutation, also assures that no point in the optimization hyper-surface has a null probability of being considered as a solution candidate, which implies that reaching the global optimal is at least possible, independently of initial guesses or how complex the pathology of the problem is. Mutation can be implemented according to different approaches depending on the coding of the chromosome (binary or real coded). The mutation strategy adopted in this paper accounts for both drastic or small changes in a particular individual, respectively called hard and soft mutation.

Hard mutation is achieved by generating an entire new individual from random values. On the other hand, soft mutation is accomplished by randomly selecting a gene of the best fit individual, i.e. one of the parameters a_0 or Ω or t_0 or α or β, and by enforcing a small variation on its value, typically by multiplying by a random number ranging from 0.9 to 1.1.

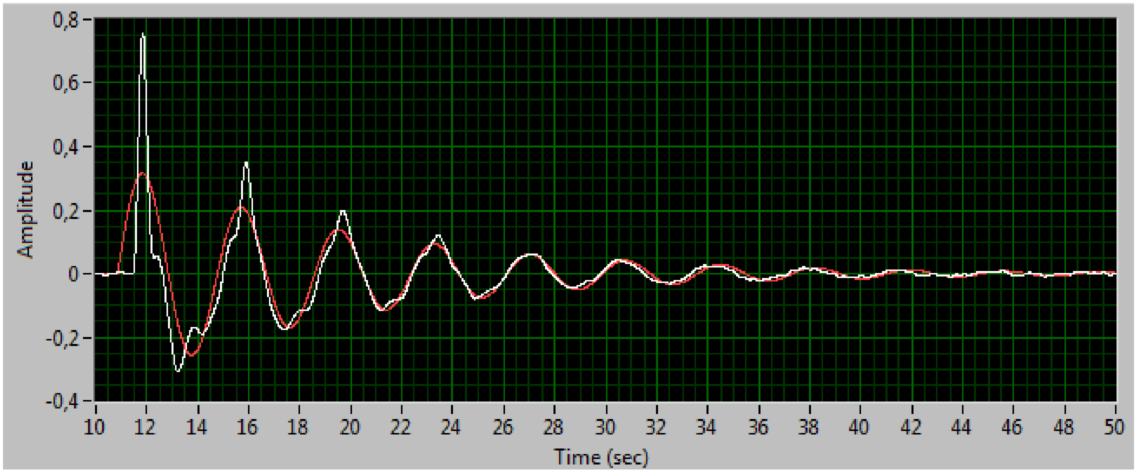

Figure 3. Model pulse $\Psi_{mod}(t)$ (red) and experimental acoustic pulse $\Psi_{actual}(t)$ (white).

5. EXPERIMENTAL FACILITIES AND TESTS

Experimental tests were executed at the pilot pipeline of the Industrial Multiphase Flow Laboratory at University of São Paulo in the campus of São Carlos – SP. This circuit, shown in the following figure, is capable of simulating several flow regimes occurring in oil and gas pipelines and works with compressed air, water and mineral oil (Shell`s vitrea 100). Water and oil are injected by 15kW screw pumps controlled by frequency inverters. Compressed air is supplied by a 50kW screw compressor and the corresponding flow rate is imposed by servo-valves controlled by orifice plates flowmeters, as indicated in Fig.4 .The test section is constituted of 50mm internal diameter metal tubes extending through approximately 1000m between the injection pumps and the separation reservoir.

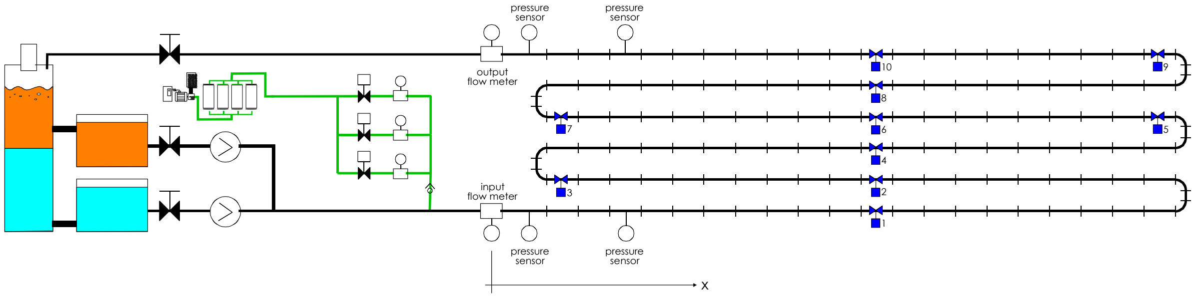

Figure 4. Schematic representation of the pilot pipeline where at the Industrial Multiphase Flow laboratory.

Four pressure sensors and two magnetic flowmeters are positioned the inlet and outlet sections of the pipeline, according to the details given in the following table. Ten solenoid valves were distributed along the pipeline and were used to simulate leaks at known positions and times. The leak`s diameter was defined with the help of 8 mm orifice plates placed between the solenoid valve and the connection to the pipeline. The leak flow rates were previously calibrated in function of the pumping power by a direct method with the help of a reservoir and a chronometer. The corresponding positions and other details are included in Tab. 1.

Table 1. Relative position of sensors and valves.

element	valve position from input (m)
magnetic flow meter	0.00
pressure sensor	7.10
pressure sensor	48.00
solenoid valve 1	85.44
solenoid valve 2	175.86
solenoid valve 3	254.24
solenoid valve 4	335.47
solenoid valve 5	378.77
solenoid valve 6	421.14
solenoid valve 7	499.42
solenoid valve 8	580.75
solenoid valve 9	624.05
solenoid valve 10	666.84
pressure sensor	704.23
pressure sensor	745.09
magnetic flow meter	749.16

A National Instruments electronic hardware is used for acquisition of all test and process signals (temperatures, pressures, flow rates, etc.), as well as for generating all command signals to pumps, solenoid valves, and so on. Specifically, a PXI1000B chassis equipped with a NI8176 controller module (500MHz Pentium processor) runs the experiment driver written in LabView. The PXI chassis is equipped with NI6025E modules through which all input and output signals are A/D converted. The experiment driver executes cyclically several operations in order to assure that each experimental test is executed precisely the same way. A typical experimental cycle is as follows:

1. set water pump frequency and open leakage simulation valve
2. wait for 30 seconds
3. start acquisition of test signals (pressure and flow rates)
4. wait for 10 seconds
5. close exit valve to produce a water hammer
6. wait for 70 seconds
7. stop acquisition of test signals
8. store data in an ascii file

In this paper, thirteen pump frequencies and eleven leak positions (valve 0, valve 1 …valve10) were simulated in triplicate to constitute a total of 429 experimental tests, the duration of each corresponding to 110 seconds, the whole experiment cycle ongoing for thirteen hours approximately. Valves 1 through 10 correspond to those referenced in Tab.1.Valve 0 does not actually exists and is introduced in the experimental cycle only to generate a reference to leak test. Sampling frequency was set to 120Hz and, except for analogical anti-aliasing filters, no pre-processing was applied to the test signals and they were stored as acquired.

6. SIGNAL PROCESSING

The process signals were evaluated through software developed in LabView based on genetic algorithms as described above. For the case studied in this paper, for the signal of the different pump frequencies relating to each solenoid valves acquired for each pressure sensor, was processed ten times. Then, with the results of all the parameters, the average of the attenuation coefficient parameter was calculated, with the averages the graphs shown in the results and discussion was generated.

7. RESULTS AND DISCUSSION

The analysis of the pulses obtained experimentally, shows that the wave central frequency is about 0,396 Hz, with dispersing around 0,117 Hz. This shows that the frequency of the pulse seems to be almost constant throughout the experiment. Moreover, considering the speed of propagation of the sound of 1342 m/s, resulting in an average wavelength $\lambda = 3388$ m approximately, according to the fundamental wave equation.

If a leak exists somewhere in a pipeline, the measured pulse will be different from the one measured without leak (valve position 0 m), in this case the attenuation coefficient (α) reaches values higher than one measured initially (without leak).

Figures 5, 6, 7 and 8 show that for all pressure sensors the attenuation cofficient values (α) measured for each valve are higher than the measured attenuation coefficient without leak and roughly follow a linear tendency. The observed behavior of the parameter (α) indicates the leak existence. Therefore, these results suggest that the new technique used in this study can be a reliable method for leak detection and position.

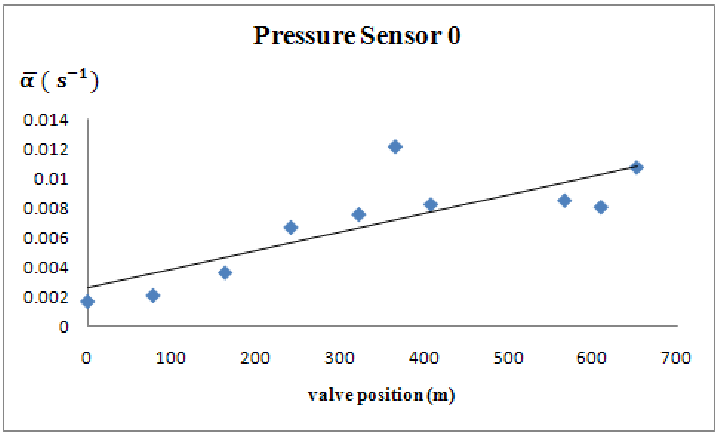

Figure 5. Average attenuation coefficient against valve position for pressure sensor 0.

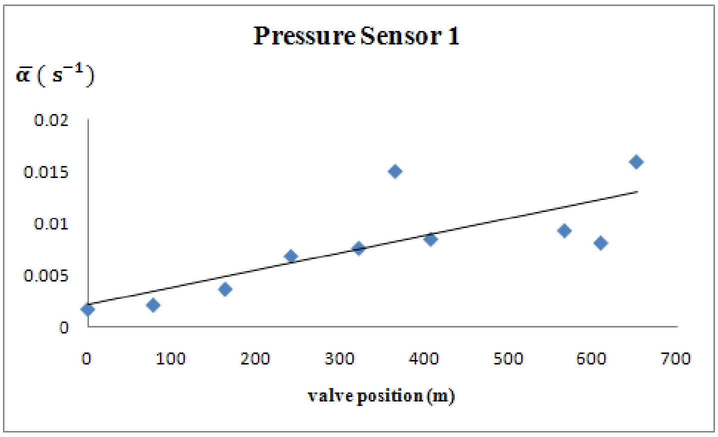

Figure 6. Average attenuation coefficient against valve position for pressure sensor 1.

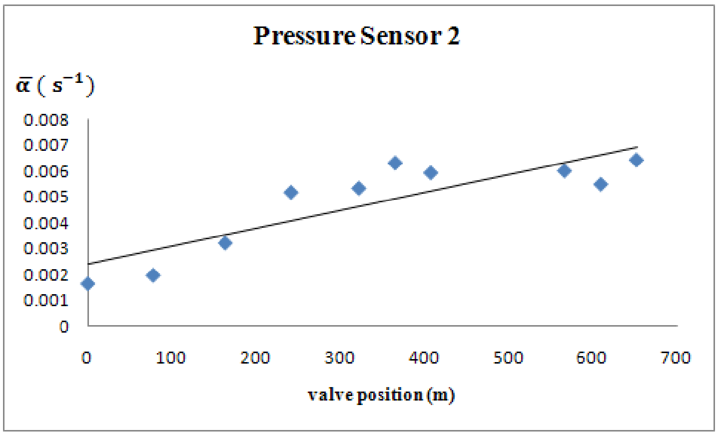

Figure 7. Average attenuation coefficient against valve position for pressure sensor 2.

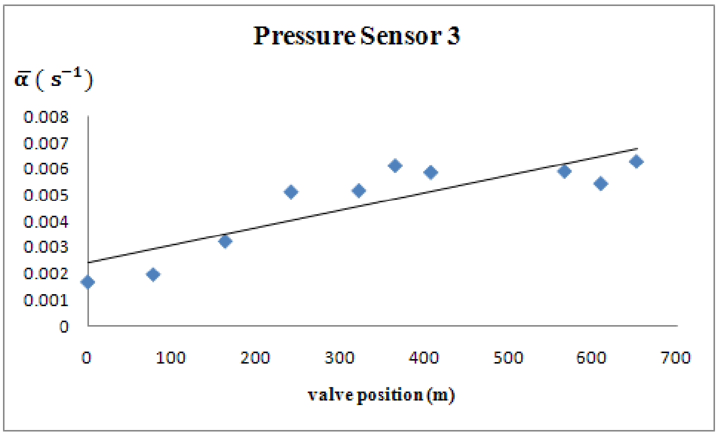

Figure 8. Average attenuation coefficient against valve position for pressure sensor 3.

8. CONCLUSIONS

In the present paper, an acoustic inspection method for detecting pre-existing leaks in liquid transportation pipelines was studied. The acoustic pulses were analyzed through a specially designed signal processing software.

The results after the processing reveal that the behavior of these parameters, particularly of the attenuation and frequency modulation ones, are indicative of the leak existence and position and, thus, can be used in an on-line LDS system.

9. ACKNOWLEDGEMENTS

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