NUMERICAL MODEL TO SIMULATE PRESSURE WAVES PROPAGATION IN PIPELINES FOR THE TRANSPORTATION OF LIQUIDS

Fernanda Olegario dos Santos, feroleg@sc.usp.br
Paulo Seleghim Jr., seleghim@sc.usp.br
Universidade de São Paulo
Escola de Engenharia de São Carlos
Av. Trabalhador Sancarlense, 400
13566-590 São Carlos – SP / Brazil

Abstract. *The analysis of hydraulic transients has been particularly useful for leak detection purposes. The basic mathematical model of a pipeline is a nonlinear distributed parameter model. The analytical solution for unsteady flow is obtained by using the equations for continuity and momentum. The application of these equations leads to a couple of nonlinear partial differential equation which must be solved numerically. This paper describes the construction and validation of a numerical model suited to the simulation of a new leak detection technique, based on active acoustic inspection of the pipeline, which is capable of detecting pre-existing leaks. Numerical results were compared to the ones obtained from experimental tests conducted at the pilot pipeline of the Industrial Multiphase Flow Laboratory at University of São Paulo, campus of São Carlos - SP. The test section is constituted of 50mm internal diameter metal tubes extending through approximately 1000m between the exit of the water pump and the entrance of the separation reservoir. Results have confirmed that the numerical model captures the correct physics of the propagation phenomena. Particularly, a good agreement was found between experimental and numerical attenuation parameters, which validates our model as an on-line predictor to be used in an LDS system.*

Keywords*: leak detection, acoustic inspection, hydraulic transient, numerical simulation.*

1. INTRODUCTION

Pipelines are considered the best means of transport of fluids. The transportation of petrochemical products through pipelines is the most common option, in both industrial applications involving long distances and 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 occurring, 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 relies 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, 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 analysis of hydraulic transients has been particularly useful for calibration and leak detection purposes. The system observation for such analysis can reveal a substantial amount of information concerning physical properties and the integrity of the system, since water hammer waves are affected by different features and phenomena, including leaks. The basic mathematical model of a pipeline is a nonlinear distributed parameter model. It describes the one-dimensional compressible fluid flow through the pipeline and is represented by a set of nonlinear partial differential equations (Streeter and Wylie, 1993). No general closed-form solution of these equations has been known yet. Numerical approaches, like the Method of Characteristics must be used instead. The objective of this work is the construction and validation of a simulator for the simulation of a new leak detection technique, based on active acoustic inspection of the pipeline, capable of detecting pre-existing leaks.

2. NUMERICAL SOLUTION OF THE NONLINEAR PIPELINE MODEL

The assumptions in the development of transient flow equations are:

1) The flow in the pipeline is considered to be one-dimensional with average velocity and uniform pressure at a section.

2) The fluid is single-phase, homogeneous and compressible (the compressibility of the fluid is incorporated into the speed of propagation of the elastic wave).
3) Variations in the density of the fluid flow and temperature during the transition are negligible compared to variations in pressure and flow.
4) Unsteady friction losses are approximated as quasi-steady state losses.
5) There is no axial motion, i.e. the fluid-structure interaction is neglected.
6) The pipe is rectilinear and horizontal, with an area of constant cross section and without lateral flow (although variations in the cross section and lateral flow can be included as control conditions).

By enforcing mass and momentum balance one obtains:

$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}-V sin\theta+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \tag{1}$$

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{fV|V|}{2D}=0 \tag{2}$$

with piezometric head *H(x)*, velocity *V(x)* , gravitational acceleration *g*, coordinate along the pipe axis *x*, time *t*, celerity or pressure wave speed *a* and Darcy-Weibach friction factor *f*.

For most engineering applications, the convective terms $V(\partial H/\partial x)$, $V(\partial V/\partial x)$ are very small compared to the other terms and may be neglected (Chaudhry, 1987). A simplified form of Eqs. (1) and (2) using the discharge $Q=VA$ instead of the flow velocity V is:

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \tag{3}$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{fQ|Q|}{2gDA^2}=0 \tag{4}$$

Equations (3) and (4) represent the nonlinear distributed parameters model of a pipeline.

2.1. Numerical solution by the method of characteristics

The method of characteristics was applied to solve the system of Eqs. (3) and (4). According to this method, the solution is given by the linear combination of these two equations, therefore $L = L_1 + \lambda L_2$. Being

$$L_1 = \frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{f}{2gDA^2}Q|Q|=0 \tag{5}$$

$$L_2 = \frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0, \tag{6}$$

thus

$$\lambda\left(\frac{\partial H}{\partial t}+\frac{1}{\lambda}\frac{\partial H}{\partial x}\right)+\frac{1}{gA}\left(\frac{\partial Q}{\partial t}+\lambda a^2\frac{\partial Q}{\partial x}\right)+\frac{f}{2gDA^2}Q|Q|=0 \tag{7}$$

The two variables *H (x, t)* and *Q (x, t)* are functions of *x* and *t*, requiring a dependency between *x* and *t*, we obtain the value of parameter λ:

$$\lambda=\pm\frac{1}{a} \tag{8}$$

Equation (7) can be expressed by

$$\frac{dQ}{dt}+\lambda\, gA\frac{dH}{dt}+\frac{f}{2DA}Q|Q|=0 \tag{9}$$

A transformation into four ordinary differential equations grouped into two pairs of equations by the method of characteristics is possible

- along the C^+ characteristic line ($dx/dt=+a$)

$$\frac{dQ}{dt}+\frac{gA}{a}\frac{dH}{dt}+\frac{fQ|Q|}{2DA}=0 \tag{10}$$

- along the C^- characteristic line ($dx/dt=-a$)

$$\frac{dQ}{dt}-\frac{gA}{a}\frac{dH}{dt}+\frac{fQ|Q|}{2DA}=0 \tag{11}$$

To satisfy these characteristics relation, the x-t grid is usually chosen to ensure $dx/dt=+a$ (stability condition).

These equations may then be integrated to yield finite difference equations, which are conveniently handled numerically.

The friction factor, explicitly used in Eqs (10) and (11), is expressed as the sum of the quasi-steady part f_q and the unsteady part f_u. The computation of the quasi-steady part f_q is straightforward, whereas the unsteady part f_u is related to the instantaneous local (temporal) acceleration $1/A(\partial Q/\partial t)$ and instantaneous convective (spatial) acceleration $1/A(a\,\partial Q/\partial t)$, i.e.,

$$f = f_q + f_u = \frac{fQ|Q|}{2DA}+k\left(\frac{\partial Q}{\partial t}-a\frac{\partial Q}{\partial x}\right) \tag{12}$$

The Brunone friction coefficient k can be predicted either empirically or analytically. The analytical definition of k using Vardy and Brown's shear decay coefficient C* (Vardy and Brown, 1996) is used in this paper:

$$k=\frac{\sqrt{C^*}}{2};\quad C^*=\begin{cases}0.0476 & \text{for laminar flow}\\ \dfrac{7.41}{\mathrm{Re}^{\log(14.3/\mathrm{Re}^{0.05})}} & \text{for turbulent flow}\end{cases} \tag{13}$$

3. LEAK DETECTION BASED ON ACOUSTIC SENSING

The sudden structural failure of a transport pipeline originates a leak that engenders a hydrodynamic transient which 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. The 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 (Martins and Seleghim, 2008).

The following figure shows the pressure signals measured at both ends of a *2000m* oil pipeline during a simulated leak test.

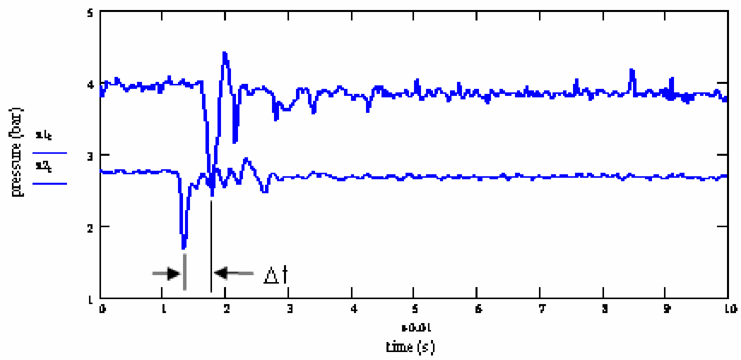

Figure 1. Characteristic pressure waveforms during a simulated leak test.

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

$$\Delta t = \int_0^{\ell} \frac{dx}{V(x) - a(x)} - \int_{\ell}^{L} \frac{dx}{V(x) + a(x)} \tag{14}$$

It is clear that to solve (14) it is necessary to supply the average flow velocity and the acoustic propagation speed profiles, which are dependent on the local temperature and pressure and must be determined from the previous equations.

The detection method used in this work is based on the active acoustic inspection of the pipeline. The basic idea of the method is to produce acoustic pulses artificially and inject them into the flow at one end of the pipeline section monitoring so that they travel to the other extreme, where a sound pressure sensor is placed to measure the corresponding signal. During this travel, the attenuation and deflection are the outcomes of the characteristics of flow and tube's geometry.

The behavior of the attenuation factor (α) indicates the existence of a leakage. If a leak exists somewhere in the acoustic path, the measured pulse will be different from the one measured prior to the existence of the leak. In other words, a leakage can be detected by assessing attenuation and deformation and comparing the corresponding parameters with a previously determined reference for cases without leakages. The value of α obtained in tests without leakage is a parameter of comparison. Furthermore, the variable α can be used to locate the leak, as the higher the value of α, the nearest the leak to the position where the acoustic pulses are produced artificially.

The equation described in (15) is used for the adjustment of numerical and experimental pulses. The parameters were adjusted using Genetic Algorithms, described in greater details in (Lima and Seleghim, 2009).

$$\Psi(t) = a_0 \sin\left(2\pi\Omega(t - t_0)^{\beta}\right) e^{-\alpha(t - t_0)}, \tag{15}$$

where a_0 represents the amplitude, Ω is the central frequency, t_0 is the delay, β is the frequency modulation exponent and α is the attenuation factor.

4. STATEMENT OF THE SIMULATION PROBLEM

The numerical software was developed together with the numerical model suitable for the simulation of a leak detection technique, based on an active acoustic inspection of the pipeline. More precisely, acoustic pulses were artificially produced and injected in to the flow at one of the ends of the monitoring pipeline section. These pulses traveled to the other end, where an acoustic pressure sensor was placed to measure the corresponding signal. During the travel from one end to the other end of the pipeline, attenuation and distortion result from the flow characteristics and pipe's geometry. If a leak existed somewhere in the acoustic path, the measured pulse would be different from the one measured prior to the existence of the leak. In other words, a leak can be detected by assessing attenuation and distortion and comparing the corresponding parameters with reference to the one previously determined without leaks.

The simulator developed for hydraulic analysis in the transitional was encoded in FORTRAN language and implemented by Force 2.0. The routines that allow the evaluation of different contour conditions are reservoir-level variable or constant, leakage and demand variables using the formulation of leaks in-line-valve and atmosphere-valve.

5. EXPERIMENTAL PROCEDURE

The numerical results were compared to the ones obtained from experimental tests conducted at the pilot pipeline of the Industrial Multiphase Flow Laboratory at University of São Paulo, campus of São Carlos - SP. The test section is constituted of 50mm internal diameter metal tubes extending through approximately 1000m between the exit of the water pump and the entrance of the separation reservoir. This experimental setup is shown in the following figure:

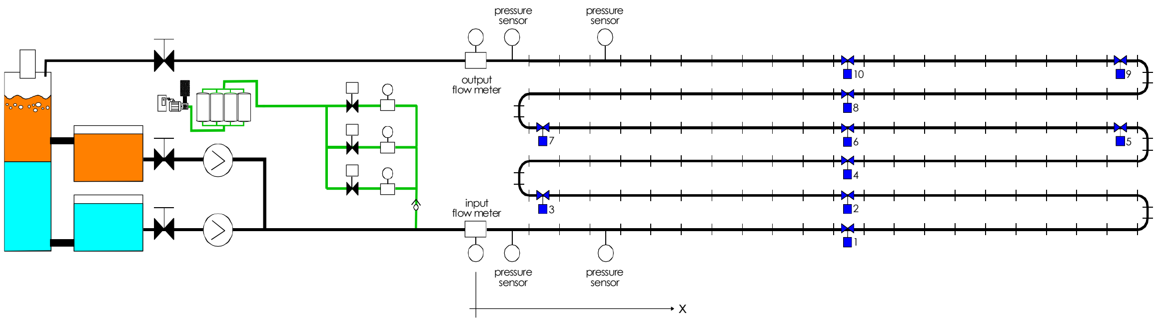

Figure 2. Schematic representation of the pilot pipeline at the Industrial Multiphase Flow laboratory.

Four pressure sensors and two magnetic flow meters were positioned at the inlet and outlet sections of the pipeline. Ten solenoid valves were distributed along the pipeline and used to simulate leaks at known positions.

In this work, 13 pump frequencies and ten leak positions were simulated in triplicate to constitute a total of 390 experimental tests. The duration of each test corresponded to 80 seconds and the whole experiment cycle took 4 and a half hours, approximately. The acoustic inspection pulses corresponded to water hammers generated by closing a fast action valve placed at the exit end of the pipeline. Both experimental and numerical acoustic inspection pulses were analyzed through a specially designed signal processing software which fitted a parameterized pulse model to the measured ones Eq.(15). The corresponding positions 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 (1)	7.10
pressure sensor (2)	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 (3)	704.23
pressure sensor (4)	745.09
magnetic flow meter	749.16
water hammer valve	764.0

A National Instruments electronic hardware is responsible for acquiring all test or 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 an NI8176 controller module (5000MHz 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 several operations cyclically in order to assure that each experimental test will be 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

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

6. RESULTS AND VALIDATION

The numerical and experimental results are presented and compared in this section. The numerical simulations were performed from the data observed in experimental tests. The numerical section is constituted of 50mm internal diameter metal tubes extending through 757m between pressure sensor 1 and the water hammer valve. Just as in the experimental tests, ten solenoid valves distributed along the pipeline were considered and used to simulate the leak in the same position known in the tests the pressure values were obtained in four pressure sensors, the initial contour conditions were obtained by taking the pressure and flow values generated in the test and read in the first line of the output data file. The numerical cycle is as follows:

1-Set initial conditions and contour
2-Wait until data have stabilized
3-Open valve leakage simulation
4- Wait until data have stabilized
5-Start logging
6-Close exit valve to produce a water hammer
7- Wait until data have stabilized
8-Stop logging
9-Store data in an ASCII file.

The results for a transient event of 80s are shown in Figs. 3, 4, 5 and 6, at the point where the pressure sensors are located according to Tab. 1, considering the following cases: (i) experimental data, in Figs. 3 and 5; (ii) linear elastic model considering Brunone friction factor with variable damping coefficient $k = 0.10$ in Figs. 4 and 6.

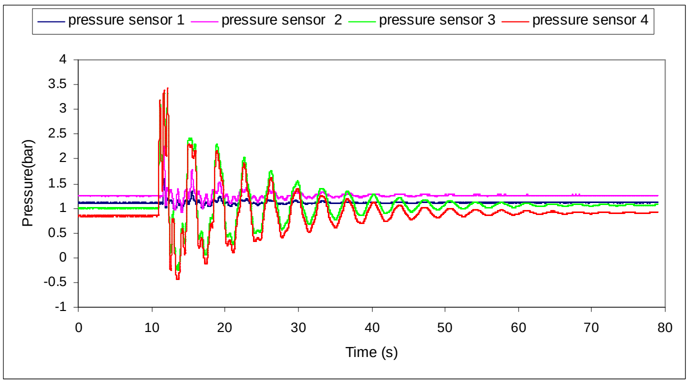

Figure 3. Experimental results in a pipeline without leak.

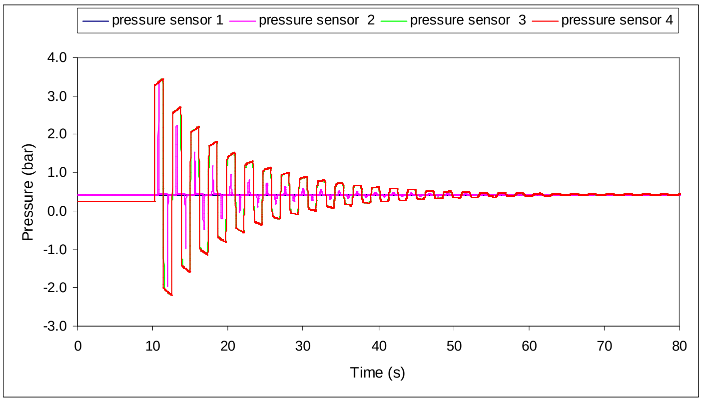

Figure 4. Numerical results in a pipeline without leak.

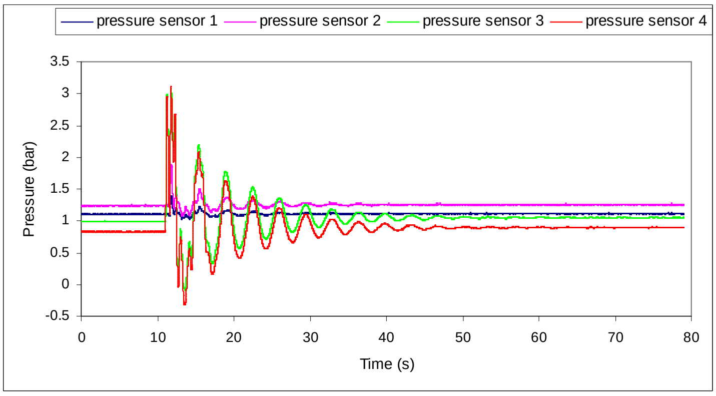

Figure 5. Experimental results in a pipeline with a leak in solenoid valve 1.

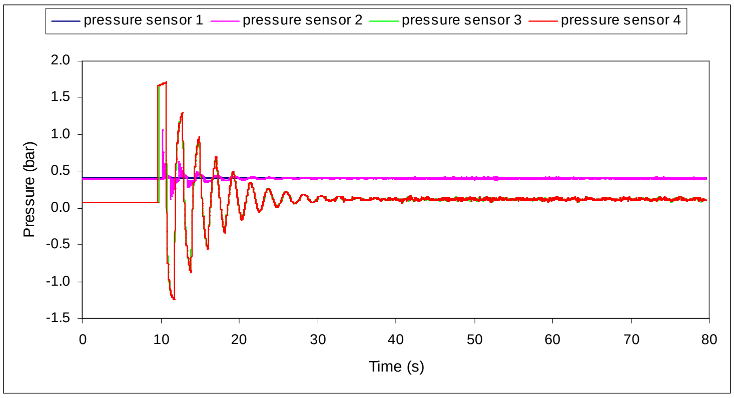

Figure 6. Numerical results in a pipeline with a leak in solenoid valve 1.

Figures 7 and 8 show the results of the experimental tests and computational simulation, for the computational model considering a variable factor friction and constant factor friction equal to 0.1 and 0.2 The Fourier transform filter was utilized to extract the average value from the signal.

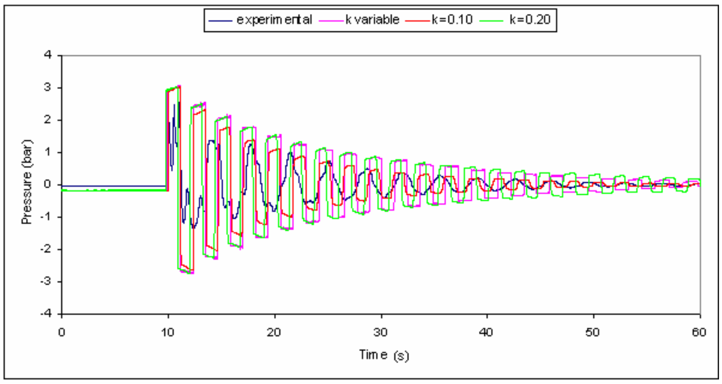

Figure 7. Comparison between numerical and experimental results in the pipeline without leak.

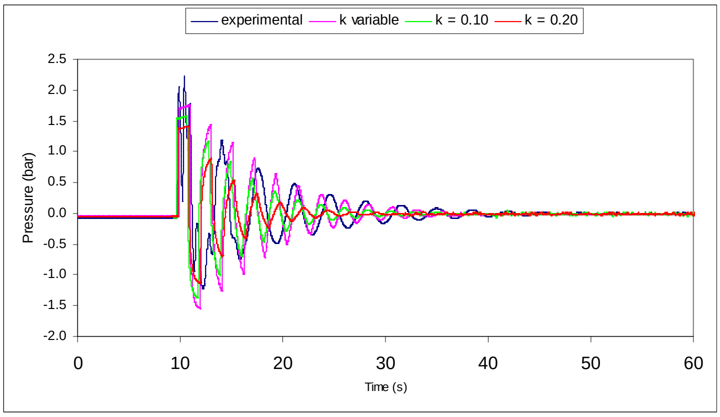

Figure 8. Comparison of numerical and experimental results in the pipeline with a leak in solenoid valve 1.

The numerical results presented a good agreement with the attenuation parameter of the experimental tests confirming that the numerical model captured the correct physics of the propagation phenomena.

Analyzing the transient flow caused by closing the valve, we observed that the attenuation of pulses of pressure in the case of leakage is higher compared to the system without leaks, and the stabilization of the flow is faster in systems with leaks. The differences in frequency of waves between the numerical and experimental results are due to spurious frequencies found in the experimental results caused by the resonance of the pipe and other factors that are assumed in the development of the equations of water hammer. In the figures comparing the experimental and numerical results where the Fourier transform was applied, different values of *k* were assessed. It was possible to observe that the pressure variation presents a higher attenuation as the damping coefficient increases.

The results obtained via hydraulic simulator were used in the numerical model suited to the simulation of leak detection technique.

Figure 9 shows the variation of the attenuation coefficient (α) for the experimental and numerical tests.

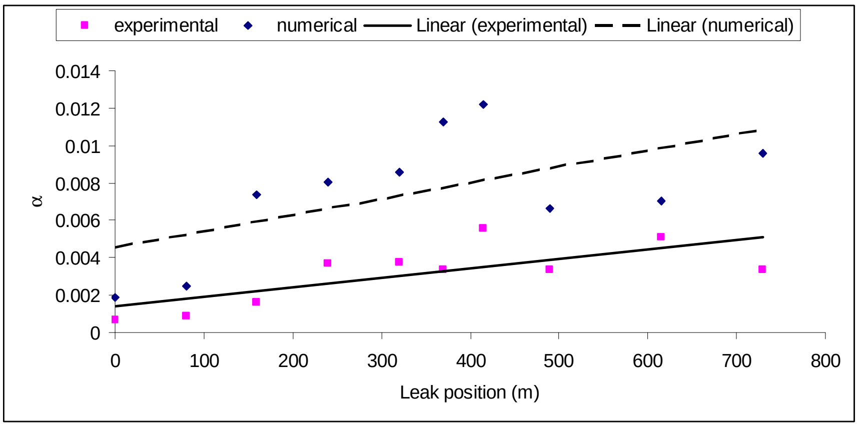

Figure 9. Detection obtained in experimental and numerical results (α at $x=0$ represents no leak).

In Fig. 9 position $x= 0$ corresponds to the test without leaking and has a natural attenuation of tubing. The numerical value at this point is very close to the experimental value. For other positions there is a significant difference between the numerical and experimental results (the number overestimates the attenuation), but qualitatively the trends are similar. In the numerical result there is a strong deviation from the average trend, which requires more testing to be explained or corrected.

The results have shown that besides being a good indicator of the existence of leakage, the attenuation coefficient also allows its location. From Fig. 9 it is possible to observe that the attenuation coefficient increases for the simulation without leakage, i.e. all values of leaks appeared to be larger than the experiment without leakage, showing that variable α can be used as a parameter to detect leakages. Furthermore, the variable can be used to locate the leakage, through at the calibration previously made by the simulator.

7. CONCLUSIONS AND PERSPECTIVES

The construction and validation of the simulator developed for transient hydraulic analysis in the numerical model suitable for the simulation of a leak detection technique have been presented. The results confirmed that the numerical model captures the correct physics of the propagation phenomena. Particularly, a good agreement was found between the experimental and numerical attenuation parameters, which validates our model as an on-line predictor to be used in an LDS system.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by CNPq (Proc 142523/2006-2.) and FAPESP (proc 2007/08555-0).

9. REFERENCES

Allen R. L. and Mills D. W., 2004, "Signal analysis time, frequency, scale, and structure", John Wiley & Sons, Inc., Publication, 937p.

Bergant, A., Simpson, A.R. and Vítkovský, J., 2001, "Developments in unsteady pipe flow friction modelling", Journal of Hydraulic Research, Vol 39, no.3.

Botrosa, K.K., Geerligsa, J. and Zhoub, J., Gloverb, A., 2007, "Measurements of flow parameters and decompression wave speed following rupture of rich gas pipelines, and comparison with GASDECOM", International Journal of Pressure Vessels and Piping, N.84, pp.358–367.

Brunone, B., Golia, U. M. and Greco, M., 1991, "Modelling of Fast Transients by Numerical Methods", In: CABRERA, E.; FANELLI, M. (eds.): Proceedings of the International Meeting on Hydraulic Transients and Water Column Separation, Valencia, Spain, p. 273-280.

Chaudhry, M.H., 1987, "Applied hydraulic transients", Van Nostrand Reinhold Company, New York, USA.

Chuanhu G., Guizeng, W. and Hao, Y., 2008, "Analysis of the smallest detectable leakage flow rate of negative", To appear in: Computers and Chemical Engineering.

Duck, f. A.; Baker, A.C.and Starritt, H. C., 1998, "Ultrasound in medicine". Institute of Physics, 336p.

Ghidaoui, M. S., Zhao, M., Mcinnis, D. A. and Axworthy, D. H.,2005, "A Review of Water Hammer Theory and Practice. Applied Mechanics Reviews, v. 58, p. 49-76, Jan.

Matko, D., Geiger, G.,Gregoritza, W., 2000, "Pipeline simulation techniques", Mathematics ande Computers in Simulation, 52, 211- 230.

Silk, M. G., and P. Carter, 1995, "A Review of Means of Pipeline Leak Detection Independent of Flow Measurement", EC Project DE-PIRE DGXII Meeting, Harwell, UK .

Soares, A. K., 2007," Calibração e detecção de vazamentos em modelos de sistemas hidráulicos no escoamento transitório". São Carlos, 2007. Tese (Doutorado),Escola de Engenharia de São Carlos, Universidade de São Paulo.

Sparrow, E.M., 1980, "Forced Convection Heat Transfer in a Duct Having Spanwise-Periodic Rectangular Protuberances", Numerical Heat Transfer, Vol.3, pp. 149-167.

Streeter, V.L., Wylie, E.B, 1995, "Fluid Transients in Systems", Prentice Hall, London.

Szirtes G., Póczos B. and András Lőrincz, 2005, "Neural Kalman filter, Neurocomputing," Volumes 65-66, pp.349-355.

Vardy, A.E., and Brown, J.M.B., 1996, "On turbulent, unsteady, smooth-pipe flow", Proc., Int. Conf. on Pressure Surges and Fluid Transients, BHR Group, Harrogate, England, 289 – 311.

Vítkovský, J. P., Lambert, M. F., Simpson, A. R. and Bergant, A., 2000, "Advances in Unsteady Friction Modelling in Transient Pipe Flow", In:VII International Conference on Pressure, Vol.39, pp. 471-482.

Zielke, W, 1968, "Frequency-dependent friction in transient pipe flow". Journal of Basic Engineering, ASME, 90(1), 109 – 115.

10. RESPONSIBILITY NOTICE

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