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Procedia Engineering 00 (2013) 000–000

Procedia Engineering

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12th International Conference on Computing and Control for the Water Industry, CCWI2013

A stochastic tool for determining the presence of partial blockages in viscoelastic pipelines: first experimental results

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Abstract

Partial blockages in water pipe networks may contribute to large energy dissipation throughout the system and reduce the service effectiveness for the customers. In this paper, a recently developed stochastic model using transient head measurements for detecting partial blockages in water pipelines is tested with two experimental case studies. The model is a stochastic Successive Linear Estimator (SLE, Yeh et al. 1996) previously used in groundwater hydrology for detecting the heterogeneity pattern of the subsurface. The model provides statistically the best unbiased estimate of diameter distribution due to partial blockages and quantifies the uncertainty associated with these estimates. Tests were carried out at the Water Engineering Laboratory of the University of Perugia (WEL) on two high density polyethylene pipe systems. In the experiments the partial blockages were simulated by placing a smaller diameter pipe of two different lengths between the main pipe. Results show that a first good estimate of the length and the size of the blockage can be obtained by a single short duration transient test executed by maneuvering a ball valve located far away from the blockage position.

Keywords: Pipe systems diagnosis; Viscoelastic pipes, Stochastic Linear Estimator.

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1. Introduction

Partial blockages in pipelines introduce relevant energy dissipation throughout the system and increase the number of disservices for the customers. The problem is of particular interest in waters supersaturated with calcium and in colder climates where freezing phenomena can cause the partial or even the complete occlusion of the pipes. A prompt detection of these anomalies is paramount to take quick remedial actions which provide the requested performance of the pipe system.

Over the past decades, transient test based techniques have been proposed as a tool of diagnosis (e.g., Liggett and Chen 1994; Brunone 1999; Vítkovský et al. 2000; Brunone and Ferrante 2001; Kapelan et al. 2003; Ferrante and Brunone 2003; Mohapatra et al. 2006; Lee et al. 2008; Meniconi et al. 2010, 2011a,b, 2012a,b; Duan et al. 2012). In particular, in partial blockage detection different methods have been developed that can be classified with respect to the domain and the duration of analysis, and to the hydraulic simulation of the partial blockage. Within the hydraulic simulation of the partial blockages early papers simulated the blockage as a partially closed in-line valve (discrete blockages), while only recently, the blockage has been modeled with a smaller diameter pipe to consider situation in which the partial blockage can affect significant stretches of the pipe relative to the pipe length (i.e., extended blockage, Brunone et al. 2008, Meniconi et al. 2011b; Duan et al. 2012). However, such simple geometries may be not yet consistent with the reality where blockages randomly occur in the pipes with different sections, different lengths and unknown geometries.

In this paper we used a novel approach by simulating the partial blockage with a distribution of unknown diameters of the pipe (Massari et al. 2013a). Unlike previous approaches, the partial blockage detection focuses on the estimation of the diameters describing the partial blockage geometry, rather than of inferring its length and its size. As estimation method we use the Stochastic Linear Estimator algorithm developed by Yeh et al. (1996) and Zhang and Yeh (1997) in groundwater hydrology to estimate large parameter fields, and, recently used by Massari et al. (2013a, 2013b, 2013c) for the diagnosis of pipe systems. We carried two experimental tests on the Water Engineering Laboratory of the University of Perugia (Italy), WEL, on high density polyethylene pipes (HDPE). We show that the presence of the blockage, experimentally created by a pipe of a smaller diameter pipe, can be detected estimating the diameter distribution of the pipe.

2. Experimental setup

Experimental tests at WEL were executed on two different high-density polyethylene (HDPE) pipe systems (BL1 and BL2) supplied by a constant head tank (Figure 1).The total pipe system length is L_{BL1}= 168.49 m and L_{BL2} = 171.53 m, respectively. They consist of three pipes in series: the upstream main pipe, that links the tank to the second pipe, has a diameter equal to D_1=933 mm and a length L_1 =62.23 m. The central pipe – that aims to simulate the partial blockage − has a diameter D_2 = 38.30 mm, DN50 and lengths L_2 = 3.56 m (BL1) and 6.6 m (BL2), respectively. The downstream main pipe has a diameter D_3=D_2 and length L_3 = 110.44 m, and links the blockage to the end valve V (Figure 1). According to the steady-state flow direction, the Upstream Connection (UC) − i.e. the connection between the upstream main pipe and the long blockage − is a sudden contraction, whereas the Downstream Connection (DC) is a sudden enlargement. The main measurement section, hereafter referred to as section M, is placed immediately upstream of the maneuver valve V. In order to study the interaction between pressure waves and the blockage and the consistency of the acquired pressure signals, other measurement sections were placed in the system (sections N, P and S) but they were not used in this study.

For each pipe system the transient test was generated by the fast and complete closure of the end valve (T_{manBL1} = 0.08 s and T_{manBL2} = 0.065 s). The pressure signal, h, is acquired by piezoresistive transducers at a frequency of 1024 Hz. The steady-state discharge (equal to 2.4 l/s and 2.7 l/s, respectively) is measured by means of an electromagnetic flowmeter. The pressure signals were filtered by means of a wavelet filter implemented in ©Matlab. Table 1 shows a detail description of the geometry and the characteristics of BL1 and BL2 pipe systems along with their respective transient tests.

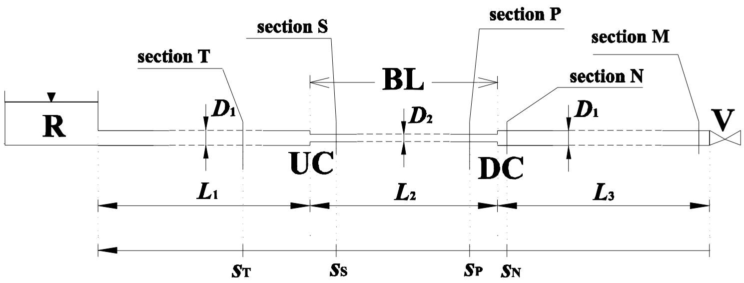

Fig. 1. Sketch of the experimental set-up used for systems BL1 and BL2.

Table 1. Summary of the geometry and characteristics of the transient test executed in BL1 and BL2 pipe systems. *L* and *D* refer to the length and the diameter of the pipes while q_0 and h_0 initial discharge and the hydraulic head of the system. T_{man} is the time of the manoeuvre.

	BL1		BL2	
L_1, D_1	54.49 m	0.0933 m	54.49 m	0.0933 m
L_2, D_2	3.56 m	0.038 m	6.6 m	0.038 m
L_3, D_3	110.44 m	0.0933 m	110.44 m	0.0933 m
L_{tot}	168.49 m		171.53 m	
T_{man}	0.08 s		0.065 s	
Acquisition Rate [Hz]	1024		1024	
Duration [s]	1		1	
q_0 [l/s]	2.4		2.7	
h_0 [m]	19.6			

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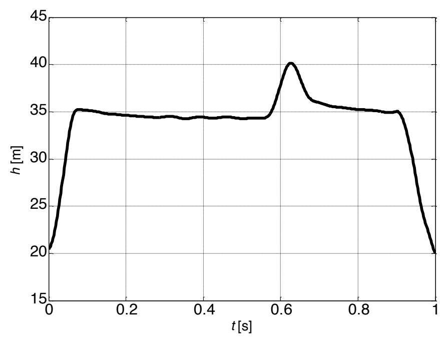

Fig. 2. Pressure signal recorded at section M.

3. Methods

3.1. Forward model

The 1-D unsteady flow of a compressible liquid in a viscoelastic pipe can be simulated by means of the following equations (Ghilardi e Paoletti 1986):

$$\frac{\partial h}{\partial t}+\frac{(a^i)^2}{gA}\frac{\partial Q}{\partial x}+\frac{2(a^i)^2}{gA}\frac{d\varepsilon^r}{dt}=0$$
$$\frac{\partial h}{\partial x}\frac{Q}{gA^2}\frac{\partial Q}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+J=0 \quad (1)$$

in which x = axial co-ordinate, t = time, A = pipe area, g = gravitational acceleration, a_i = elastic pressure wave speed (with the superscript i indicating the instantaneous value), J = friction term, h = pressure head and Q = discharge. In Eq. (1) the additional the derivative of the retarded strain, ε^r ,takes the effect of the rheological behavior due to the retarded increasing deformation occurring during the application of a constant stress in viscoelastic materials. The quasi steady approach has been used to evaluate the friction term J since attention is focused on the first phases of the transients (Brunone and Berni, 2010). The assumption can be considered acceptable since in this paper the diagnosis is carried out within the short period analysis approach. For further details on the terms of Eq. (1) the reader is referred to Meniconi et al. (2012a,b).
The head and discharge values are calculated by discretizing and solving the problem by the method of characteristics leading to a matrix form similar to that one proposed by (Liggett and Chen 1994).

$$\{u\}=[M]^{-1}\{R\} \quad (2)$$

where $[M]$ is the coefficient matrix, $u=\{h \quad Q \quad \varepsilon^r\}^T$ the solution vector of the heads, discharges and the strains and $\{R\}$ the vector associated with the boundary conditions. Equation (2) defines a non-linear system of equations and must be solved at every time step.

3.2. Inverse model: SLE

In this study SLE is used for estimating the diameter distribution of the pipe following the same method used by Massari et al. (2013b). The algorithm assumes the pipe diameter, D as a stationary stochastic process with a constant unconditional mean $Y_d=E[\ln D]$ and unconditional log-perturbation $d(x)$, i.e. $\ln D(x)=Y_d+d(x)$, ($E[\bullet]$ denotes the expected value operator). The corresponding head, h, is given by $h(x)=\Phi(x)+\phi(x)$ where $\Phi(x)=E[h(x)]$ is the mean of $h(x)$ and $\phi(x)$ the unconditional head perturbation. A first estimate of $d(x)$, is obtained by a linear combination of the weighted observed values of d and ϕ . That is,

$$\hat{d}(x_0)=\sum_{k=1}^{N_\phi}\beta_{dk}\phi(x_k) \quad (3)$$

where $\hat{d}(x_0)$ is the cokriged value at location x_0 and N_ϕ is the number of observed heads. The weights β_{dk} are evaluated by requiring that the estimation expressed by Eq. (3) will have a minimum variance. The latter leads to a linear system of equations in terms of the covariance matrix $[C_{\phi\phi}]$, and the cross-covariance matrix, $[C_{\phi d}]$

$$\sum_{pj=1}^{N_d}\lambda_{dj}C_{d\phi}(x_k,x_{pj})+\sum_{pk=1}^{N_\phi}\beta_{dk}C_{\phi\phi}(x_k,x_{pk})=C_{\phi d}(x_k,x_0) \quad (4)$$

The covariance $[C_{\phi\phi}]$ and the cross-covariance $[C_{\phi d}]$ in Eq.(4) are derived by the first-order numerical approximation (Dettinger and Wilson, 1981). The values of the diameter are then obtained by $D(x_0)=\exp[d(x_0)+Y_d(x_0)]$. SLE also allows the calculation of the uncertainties associated with the estimates by evaluating the conditional covariance:

$$\varepsilon_{dd}^{(1)}(x_0,x_0)=C_{dd}(x_0,x_0)-\sum_{k=1}^{N_\phi}\beta_{dk}C_{d\phi}(x_k,x_0) \quad (5)$$

In Eq. (5) [C_{dd}] is the covariance matrix of diameters that can be suggested or estimated from the knowledge of the primary information.
To account for the non-linear relationship between d and h not embedded in the cokriging, SLE is used. That is,

$$\hat{Y}_d^{(r+1)}\left(x_0\right)=\hat{Y}_d^{(r)}\left(x_0\right)+\sum_{j=1}^{N_\phi}\omega_{j0}^{d}\left[h_j^*\left(x_j\right)-h_j^{(r)}\left(x_j\right)\right] \tag{6}$$

where ω_{j0}^d are weighting coefficients to estimate the diameter at location x_0 with respect to the head measurements at location x_j and r is the iteration index. $\hat{Y}_d(x_0)$ is the estimate of the conditional mean of $\ln D(x_0)$, h_j^* is the observed head at location x_j, and $h_j^{(r)}$ is the simulated head at the same location based on the estimates at the r^{th} step. The weights ω_{j0}^d are selected by requiring the minimum variance of Eq. (6).
The conditional covariances are evaluated according to:

$$\varepsilon_{dd}{}^{(r+1)}\left(x_0,x_k\right)=\varepsilon_{dd}{}^{(r)}\left(x_0,x_k\right)-\sum_{i=1}^{N_\phi}\omega_{i0}^{d(r)}\varepsilon_{d\phi}^{(r)}\left(x_i,x_k\right) \tag{7}$$

which allows to evaluate the accuracies of the estimate $\varepsilon_{dd}\left(x_0,x_0\right)$ at each iteration. The smaller $\varepsilon_{dd}\left(x_0,x_0\right)$ is, the more accurate the estimate. After obtaining the value of $Y_d\,(x_0)$, the governing equations are solved again with the new value of $Y_d(x_0)$ leading to new head data $\{h\}$; then, appropriate norms of the parameters and of the heads are evaluated. If the norms are smaller than the prescribed tolerances, the iteration stops, otherwise Eqs. (2) and (6) are solved again. For further details of the algorithm the reader is referred to (Yeh et al. 1996, Massari et al. 2013a,b,c).

3.3. Forward model setup and calibration

To calibrate the 1-D numerical model two sets of parameters were determined: those describing the viscoelastic behaviour of pipe material and those related to the flow field (e.g., manoeuvre characteristic, friction factor). In this paper, a procedure similar to that one followed by Meniconi et al. (2012a,b) was adopted. In particular: (i) for the friction factor, f, the Blasius relationship was used because it supplies good results for the considered pipe systems (Brunone and Berni, 2010); ii) for the manoeuvre, the value of the discharge to assign at the valve V was calculated by means of the recorded pressure at section M during the manoeuver and the negative characteristic equation at V; iii) for the tank the recorded pressure at R was set at the last section of the pipe (note that due to the small volume of the tank, its level can be affected by the transient determining a deterioration of the results), and, (iv) all viscoelastic parameters were evaluated in a single constant diameter pipe (D = 0.0933 m) and then exported to the other setups. Further details concerning the estimation of the parameters of the model can be found in Meniconi et al. (2012a,b). In the estimation procedure, as initial guess, the pipe system total length of BL1 and BL2 was divided in 400 elements with a constant diameter D = 0.0933 m. The pressure wave speed was assumed for all elements equal to 377.15 m/s.

4. Results and discussions

4.1. System BL1

To estimate the pipe diameters SLE converged in 36 iterations with a computational time of almost 2 days (CPU Intel Core Duo 2.16 Ghz, RAM 4 Gb). Figure 2 compares the contour plot of the true and the estimated diameters along the location x of the pipe. The darker the color is the smaller the diaemeter. From this figure it can be seen that the pattern of the diameter distribution is satisfactorly detected although the estimation is less precise to infer diaemeter sharp variations. The latter is mainly due to the model structure errors and to the simplicity of some assumptions such as of the one of constant wave speed for all the pipes.

In Figure 3 the relative percentage errors $\Delta_d = (D_{tr} - D_{est}) \times 100 / D_{tr}$ between true D_{tr} and estimated D_{est} diameters are plotted. The minimum value obtained for the diameters located at the blockage position is 0.0474 m with a relative percentage error of 23 % whereas the maximum error is about 50% and occurs close to the section changes. From location x=0 to about x=110 m the noise present in the pressure signal reflects on the estimated diameters producing some oscillations of the estimates around the true value with relative errors ranging around 10% (about 1 cm). After the blockage the oscillations errors are larger likely due to the not well modelled wave scattering between the blockage and the tank.

To sum up the errors affecting the estimated diameters are are both due to the noise of the pressure signal and the following model structure errors: i) quasi-stationary approach for the friction factor evaluation, ii) constant wave speed along the entire pipe, iii) viscoelastic parameter calibrated on a simpler pipe system, iv) straight and continuos pipeline, i.e.. it has been neglected the presence of the curves, constraints of the conduits and junctions between the pipes and; v) minor losses at cross section changes are neglected and last but not least the discretization errors.

To have an idea of the capability of SLE in blockage positioning, as a first approximation, we can determine the length and the location associated to given relative error in the diameter sizing (see Figure 5 for further explanation and Table 2 for the results). As an example if we consider an error in sizing of 30% (corresponding to a diameter D^*=0.05 m) we obtain a length of 1.7 m (relative error of 48%) and a location of 115.6 m (relative erro of 4%). From Table 2 it can be seen that SLE provides good results to determine the location whereas less accurate results are obtained to infer the length of the blockage.

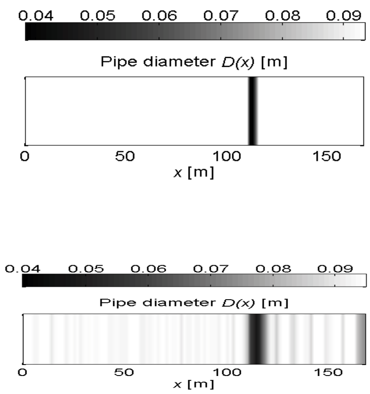

Fig. 3. BL1 pipe system: contour plot of the pipe diameter D as a function of the location along the pipe x.

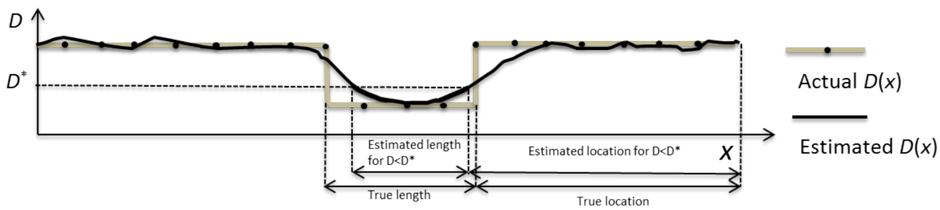

Fig. 4. BL1 pipe system: relative percentage error Δ_d between estimated and true diameters along the location x of the pipe.

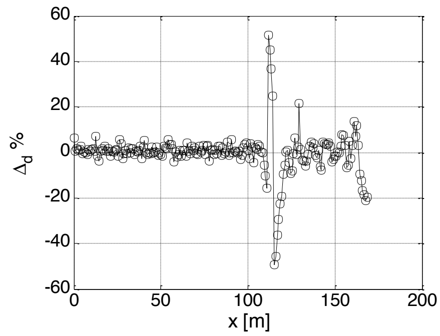

Fig. 5. BL1 pipe system: schematization of blockage length and location evaluation. D*is the diameter with a given relative error in sizing.

Table 2. BL1 system: position and location of the partial blockage inferred by the diameter distribution under a given value of the diameter $D*$.

Size relative error	Length (relative error) [m] (%)	Location (relative error) [m] (%)
(30%) $D*$=0.05 m	1.70 (48%)	115.6 (4%)
(50%) $D*$=0.06 m	5.95 (44%)	113 (2.7%)
(80%) $D*$=0.07 m	6.80 (51%)	113 (2.7%)

4.2. System BL2

For BL2, SLE converged in 26 iterations with a computational time of almost 2 days (CPU Intel Core Duo 2.16 Ghz, RAM 4 Gb). Figure 6 plots the contour plot of the true and the estimated diameters along the location x of the pipe, while the relative percentage errors are displayed in Figure 7. Results are very similar to the previous case with smooth variations of the diameter distribution at cross section changes (error up to 50%). However, in this case a better estimation of the diameter of the blockage is obtained with the smallest diameter D=0.0417 m (Δ_d = 7.5%). Better results are also obtained in the positioning as it can be seen in Table 3 with only 10% for D*<0.05 m. Such better results are probably due to the faster time maneuver used to generate transient test associated with system BL2.

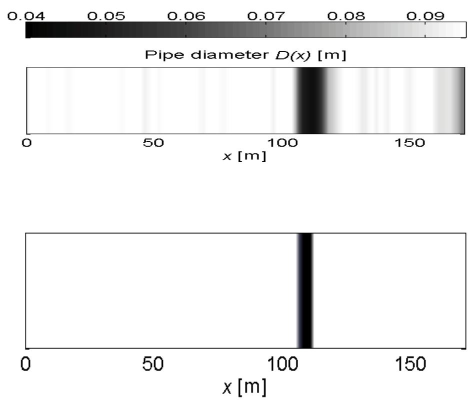

Fig. 6. BL2 system: contour plot of the pipe diameter D as a function of the location along the pipe x.

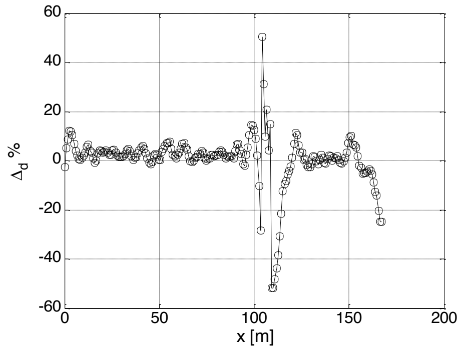

Fig. 7. BL2 system: relative percentage error Δ_d between estimated and true diameters along the location x of the pipe.

Table 3. BL2 system: position and location of the partial blockage inferred by the diameter distribution under a given value of the diameter D*.

Size relative error	Length (relative error) [m] (%)	Location (relative error) [m] (%)
(30%) D*=0.05 m	5.95 (9.84%)	107.95 (2.2%)
(50%) D*<0.06 m	8.5 (28.8%)	107.1 (3%)
(80%) D*<0.07 m	11.05 (67%)	113 (4.9%)

4. Conclusions

In this paper a stochastic linear estimator, previously used in groundwater inverse problems by (Yeh et al. 1996), was applied to detect the size and the position of extended partial blockages in polyethylene pipelines. Unlike previous approaches, SLE estimates the diameter distribution to infer the position and size of the partial blockage. The main advantage of the approach is that it can easily take into account complex geometries of the occlusions induced by blockages. Even if the transient simulation contains many structure errors, SLE is able to give a first good approximation of the size and the location of the blockages. Although further studies are needed to improve the capability of SLE and to improve the accuracy of the transient simulation, we think that the algorithm is a promising technique for blockage detection for real pipe systems.

Acknowledgements

This research has been supported by Fondazione Cassa Risparmio Perugia under the project "Hydraulic characterization of innovative pipe materials (no. 2013.0050.021)".

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