Leakage Localisation Method in a Water Distribution System Based on Sensitivity Matrix: Methodology and Real Test

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Abstract
Leaks are present in all water distribution systems. In this paper a method for leakage detection and localisation is presented. It uses pressure measurements and simulation models. Leakage localisation methodology is based on pressure sensitivity matrix. Sensitivity is normalised and binarised using a common threshold for all nodes, so a signatures matrix is obtained. A pressure sensor optimal distribution methodology is developed too, but it is not used in the real test.
To validate this methodology it has been tested with a real situation in two District Management Areas (DMA) in Barcelona. This real test only allows validating the localisation part of the methodology. Some installed sensors in these DMA have been used. For one of these DMA historical data of a leakage period is used. In the other one a leakage has been forced.

Keywords
Leakage, sensitivity, localisation

INTRODUCTION

Leakage detection and isolation may be done on a routine basis or when losses are suspected to be higher than they should be. Current used methods for locating leaks range from acoustic devices, which is the most used, to model analysis or intelligent links (Kang 2005). Some of these techniques require isolating and shut down the system to be applied. Techniques based on the analysis of pressures obtained from sensors distributed along the water network provide a more effective and less costly search of leakages.

Leakage localisation method proposed in this paper is based on pressure sensitivity matrix analysis (Pudar 1992), which gives the effect of a leak in a node to some nodes with a pressure sensor. All this methodology has been developed in PROFURED project (Landeros 2009), with AGBAR, the Water Company in Barcelona, and CETaqua, Water Technological Centre. The main objective in PROFURED project is to develop a methodology to detect and locate leaks using pressure sensors and models. Tools to develop and apply these techniques are mathematical hydraulic models of the network and flow and pressure sensor data, all of them available in a water company. All tasks defined at the beginning of this project are:

- DMA characterization in order to define some parameters to help in the selection of three pilot DMAs.
- To find drinking water patterns oriented to improve model demand characterization and demand estimation.
- Pressure sensors location, focused on a methodology to locate pressure sensors maximizing leakage detection performance.
- Leakage detection and location methodology to detect and locate leakage using pressure sensor measurements.

The DMA characterization is focused on classifying all areas depending on infrastructure (pipes material and diameters, …) and consumption (total consumption, type of consumption, …) parameters. Proposed methodology is based on a clustering process to obtain classes using these parameters as different descriptors (Pérez, de las Heras 2009).

Water demand patterns characterization is oriented to classify consumptions depending on its annual profile. The objective of this classification is to find a representative sample of each class which will provide a good estimation of total consumption of each one. Classification method used is the same as in DMA characterization. In this case descriptor used is the monthly consumption measured on each water connection. Classification obtained is compared with another one developed by the water company (Peralta 2005).

Sensor placement method has been developed using model data. Sensitivity is normalised and binarised using a common threshold for all nodes, so a signature matrix is obtained. An optimal distribution of sensors is found to maximise the discrimination in the localisation and, of course, to detect all possible leaks. This problem is solved using genetic algorithms on the basis of detection and discrimination. Thus the solution found is not the optimal one, but sub-optimal. The cost of one sensor placement solution is the number of nodes of the biggest discriminable zone (Pérez 2009a).

Leakage localisation is based on the pressure variation produced by a leakage in the network. The analytical calculation of pressure sensitivity is really complex because of the dimensions of real networks and the nonlinear equations that characterize them. Thus in this work a calculation based in a hydraulic simulation in presence and absence of leakage is proposed as an approximation of sensitivity. Localisation methodology has been tested in simulation in different situations, the ideal one and with uncertainty in demands. It is necessary to take into account that signatures matrix is not constant, because it depends on the boundary conditions related to pressures and flows in the entrances to the network or sector of the network. So for each simulation day signatures matrix is recalculated (Pérez 2009b).

Finally this methodology has been tested with two real leakage situations in different DMA in Barcelona. This is the main point of this work and an important test to conclude PROFURED's results, because it provides an evaluation of the methodology for a real situation. The first one was in *Enamorats* DMA, where a leakage was forced. The other one was in *Sta. Eulalia* DMA. For this sector some historical data about a real leakage episode was given. In both cases pressure sensors used were installed in the network, so their placement didn't use sensors placement methodology proposed.

In figure 1 case study networks are presented, *Enamorats* and *Sta. Eulalia*. They are described in section *Real Test*.

Fig. 1: Case study networks: *Enamorats* and *Sta. Eulalia*

In next section, *Fault Detection and Isolation*, the standard theory in which this work is based is explained. After that leakage localisation methodology proposed is exposed in *Leakage Localisation*. Then results obtained for the real test in figure 1 DMA's are shown in section *Real Test*. Finally, conclusions obtained are presented.

FAULT DETECTION AND ISOLATION

The methodology of leakage localisation used in this work is mainly based on standard theory of model-based diagnosis described for example in (Gertler, 1998). Model based diagnosis can be divided in two subtasks: fault detection and fault isolation. The principle of model-based fault detection is to check the consistency of observed behaviour while fault isolation tries to isolate the component that is in fault. The consistency check is based on computing residuals, $\boldsymbol{r}(k)$, obtained from measured input signals $\boldsymbol{u}(k)$ and outputs $\boldsymbol{y}(k)$ using the sensors installed in the monitored system and the analytical relationship which are obtained by system modelling:

$$\boldsymbol{r}(k) = \boldsymbol{\Psi}(\boldsymbol{y}(k), \boldsymbol{u}(k)) \tag{1}$$

where $\boldsymbol{\Psi}$ is the residuals generator function that depends on the type of detection strategy used (parity equation (Gertler, 1998) or observer (Chen and Patton, 1999)). At each time instance, *k*, the residual is compared with a threshold value (zero in ideal case or almost zero in real case). The threshold value is typically determined using statistical or set-based methods that take into account the effect of noise and model uncertainty (Blanke, 2006). When a residual is bigger than the threshold, it is determined that there is a fault in the system; otherwise, it is considered that the system is working properly. In practice, because of input and output noise, nuisance inputs and modelling errors affecting to the considered model, robust residuals generators must be used. The robustness of a fault detection system means that it must be only sensitive to faults, not to differences between the model and reality (Chen and Patton, 1999).

Robustness can be achieved at residual generation (*active*) or evaluation phase (*passive*). Most of the passive robust residual evaluation methods are based on an adaptive threshold changing in time according to the plant input signal and taking into account model uncertainty. In this paper, a passive method has been proposed for robust fault detection, where the detection threshold has been obtained using the method described for example in (Pérez 2009a). Robust residual evaluation allows obtaining a set of ***fault signatures*** $\boldsymbol{\phi}(k) = \left[\phi_1(k), \phi_2(k), \cdots, \phi_{n_\phi}(k)\right]$, where each indicator of fault is obtained as follows:

$$\phi_i(k) = \begin{cases} 0 & \text{if} \quad |r_i(k)| \le \tau_i \\ 1 & \text{if} \quad |r_i(k)| > \tau_i \end{cases} \tag{2}$$

where τ_i is the threshold associated to the residual $r_i(k)$.

Fault isolation consists in identifying the faults affecting the system. It is carried out on the basis of fault signatures, ϕ, (generated by the detection module) and its relation with all the considered faults, $\boldsymbol{f}(k) = \; f(k)_1, f_2(k), \cdots, f_{n_f}(k)$. The method most often applied is a relation defined on the Cartesian product of the sets of faults $\boldsymbol{FSM} \subset \boldsymbol{\phi} \; x \; \boldsymbol{f}$, where ***FSM*** is the ***theoretical signatures matrix*** (Gertler, 1998). One element of that matrix FSM_{ij} will be equal to one, if a fault $f_j(k)$ is affected by the residual $r_i(k)$, in this case the value of the fault indicator $\phi_i(k)$ must be equal to one when the fault appears in the monitored system. Otherwise, the element FSM_{ij} will be zero.

LEAKAGE LOCALISATION

In the process of leakage localisation, leakage signature obtained from measurements of distributed sensors is compared with signature matrix. In an ideal situation, this comparison indicates in which group the leakage is found. But in real cases the result can be unsatisfactory because of uncertainty, modelling errors or changes in boundary conditions.

This methodology has been applied in simulation and in the real case study shown in this document. Assuming that the models are not perfect, with some uncertain parameters, all tests in simulation have been done during 15 days, taking only pressure sensor values for one instant. Selected hour is the lowest consume hour, which depend on the DMA. In the lowest consume hour uncertainty is the lowest. But pressure increments due to a leakage are lower too, so methodology is more demanding from the sensor point of view. Signature obtained for each day is compared with those generated previously by moving a leakage (in the model) for all nodes to generate leakage discriminable zones. When a leakage signature is assigned to a group three options have been explored:

- Mean of sensitivities during 15 days to obtain a unique signature
- Mean of signatures
- The voting (How many days the leak is assigned to a group. That one with more assignations is the chosen group).

First results obtained using these three decision criteria where not good because of boundary conditions effects on sensitivity matrix. It is necessary to change sensitivity matrix for each day based on known boundary conditions. With signatures matrix adapted to each day, first and second criteria are nonsense, and in for the third one a new approach is proposed. A probability to have leaks is given to each node. The result of applying this method is a map of the network in different gray tones. The darker one means the greater probability.

This methodology provided perfect results for any case without uncertainty in simulation. To make the model more real uncertainty in demands is introduced. All nodes have the same demand profile, but different mean value. Some tests have been done with and 18% uncertainty, but with the same total demand. So for example, the mean demand of each node has been multiplied for a random coefficient between 0.82 and 1.18, with the constraint of keeping the total demand. Methodology applied to the case study has been adapted to the quantity of available data and model discrepancies with the reality, as is explained later.

REAL TEST

Enamorats DMA model contains 260 nodes and two water input points, where a flow meter and a pressure meter are installed. Input flows in the network and pressures at these points are fixed in the simulation model. In addition to this information this DMA have 3 installed pressure sensors, which are used to apply leakage localisation methodology. In the same way, *Sta. Eulalia* DMA contains 2132 nodes and four input points. In this case the number of installed sensors is four.

The information that the water company has provided for *Enamorats* DMA is:

- Flows and pressures with a ten minute time step for two input points during four days.
- Pressures with a ten minute time step for three pressure sensors installed during four days.
- The same information described in two first points, but for the day when the leak was forced.
- Pressures with a five second time step for the leakage day (but not for the whole day).

The information provided for *Sta. Eulalia* DMA is similar:

- Flows and pressures with a ten minute time step for two input points during fourteen days.
- Pressures with a ten minute time step for three pressure sensors installed during four days.

As it has been described in the introduction, in *Enamorats* DMA the leakage was forced. In table 1 leakage information is shown.

Table 1: Leakage information in *Enamorats* DMA

Flow[m^3/h]	Flow [l/s]	Leak location	Start time	End time
18	5	Lepant/Aragó	10:20	10:35
14	3.9	Lepant/Aragó	10:37	10:52
9	2.5	Lepant/Aragó	10:53	11:08
6	1.7	Lepant/Aragó	11:10	11:25
16	4.4	Aragó 79	11:53	12:08

In the case of *Sta. Eulalia* DMA there were detected two real leakage periods of 14 and 25 l/s mean flow. The first one was in the 15th of September 2009 and the second one in the 9th of September 2009.

The first step is to verify that the hydraulic model provided is correctly calibrated. A four days simulation without any leakage has been done taking pressure values in three internal pressure sensors. The result is the pressure evolution during each day in internal pressure sensors. Differences between the model and reality are important because of demand uncertainty. The worst consequence of these results is that pressure difference caused by a leak can be hidden. To solve this problem model is corrected with the mean error during no leakage days. Real corrected pressure using these mean errors in each sensor is shown in figure 2, compared with the simulation ones.

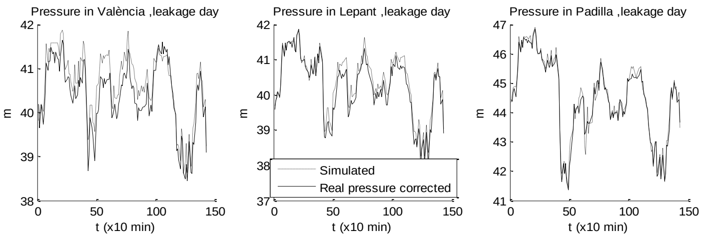


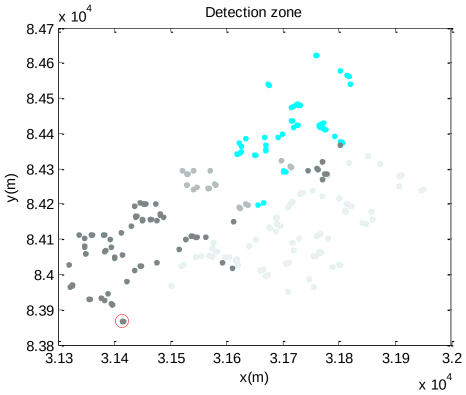
Fig. 2: Corrected real pressures compared with simulated ones.

Although a correction to real pressure has been applied no difference in the period of leakage can be observed. Thus localisation methodology is applied to see if it is possible to show more information not seen in previous figures. Leakage period duration is about one hour. For leakage period five second step time data is given by the Water Company, but only pressures, not flows. If a ten minute step time data is used, in an hour period only 6 samples can be taken. To increase the number of samples a minute step time is proposed. To calibrate the model pressures at the input points are calculated by the mean of the last 30 second data (6 samples) and input flow is taken as a constant during 10 minutes.

To find discriminable zones obtained with installed sensors a leak is moved for all 260 possible nodes using the model. For the leakage period two simulations are done: the first one without any leakage and the second one with a leakage moved for 260 nodes. Forced leakage flow is not constant, as is seen in table 1, but only ten minutes data is given for each case. For this it is assumed that the leakage flow is one of them for the whole period, 5 l/s. This assumption can be justified for the fact that in a real situation the leakage flow may be variable and unknown.

In the same way as in simulation tests, leakage methodology has been applied during more than one step time. In next figures some results are shown. The first case corresponds to the leakage period. As well as in simulation, signatures matrix has been calculated depending on boundary conditions.

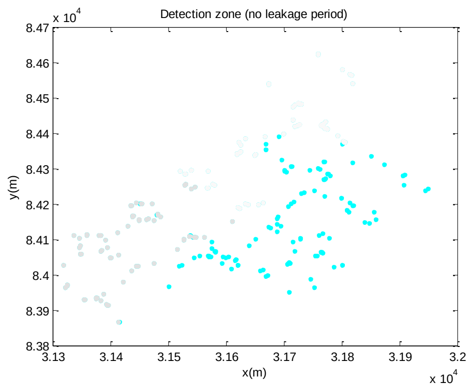
Due to the little quantity of data, the test has been done during the whole leakage period, taking a pressure measure every minute. Results for a 0.4 threshold are shown in figure 3. Although some leakages are not detectable (55 nodes zone), the real leakage is outside this zone. Sensors are not located optimally, so these undetectable leakages were expected. The number of discriminable zones is four, including the non-detectable one. Leakage zone corresponds to the third group, which contains 88 nodes.



Threshold = 0.4				
Signature			Number of nodes	Number of detections
València	Lepant	Padilla		
0	0	0	55	0
1	0	0	23	17
1	1	0	88	31
1	1	1	94	4
Total (max. = 64)				52

Fig. 3: Leakage localisation results with a threshold of 0.4 in a leakage period.

The leakage is given in the circled node. 31 of 64 detections signalled the correct leakage zone. After this test a non leakage period is chosen to apply the methodology. At night discrepancies between reality and the model are smaller than during the day, so it is the best time to do the test. Although an important zone is signalled as a possible leakage zone, number of detections is only 9 on 42. These results are shown in figure 4.



Threshold = 0.4				
Signature			Number of nodes	Number of detections
València	Lepant	Padilla		
0	0	0	29	0
0	0	1	94	0
1	0	0	62	4
1	1	0	75	5
Total (max. = 42)				9

Fig. 4: Leakage localisation results with a threshold of 0.4 in a non leakage period.

For *Sta. Eulalia* DMA the same methodology has been applied. Leakage periods data are shown in table 2. In this case only ten minute step time data is available, so the number of pressure samples to apply the localisation technique is really low, 6 in the first episode and 2 in the second one.

Table 2: Leakage information in *Sta. Eulalia* DMA

Day	Start time	End time	Mean flow
09/09/2009	16:35	17:30	25 l/s
15/09/2009	12:15	12:30	14 l/s

Detection results for the first and the second episodes are shown in figure 5. Although the leakage is inside the detection zone in both cases (in the circled zones), it is not situated in the most probable zone.

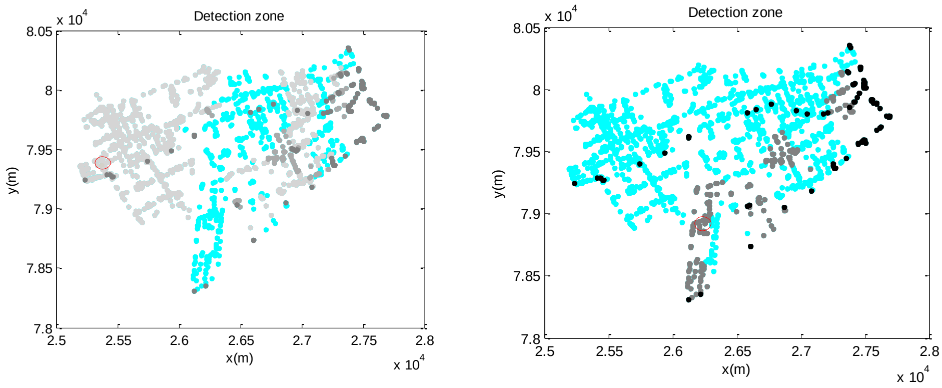


Fig. 5: Leakage localisation results for the first and the second leakage period in *Sta. Eulalia*.

Because of the low quantity of data for this case no more analysis have been done in *Sta. Eulalia* DMA.

CONCLUSIONS

A leakage localisation method based on pressure measurement and pressure sensitivity analysis proposed in PROFURED project has been tested for real leakage scenarios. This methodology is founded in standard fault detection and isolation techniques described in *Fault Detection and Isolation* section.

Previous sensors placement methodology developed hasn't been tested in case study DMA. To test sensors placement methodology an investment is necessary, so some sensors already installed are used.

This real test has shown some problems not found in simulations previous tests, in which demands uncertainty was introduced to approach ideal situation to a real one. Some results obtained are shown in *Simulation Results* section. The main problem found in real situations tested is related to the model calibration, possibly in demands estimation. Differences between the model and the reality indicate that a previous calibration of the model is necessary. Maybe some work done in PROFURED project in consumer's characterization can help in this calibration task. The objective is to find a better demand distribution and better consumer profiles.

Another problem found during the development of this methodology is related to pressure sensor sensitivity. Simulation results indicate that very low pressure increase or decrease between leakage and non leakage situation may be detected, sometimes under minimum real sensors precision. Finally quantity of data available has limited a little bit capacity of testing this methodology. Regardless all these problems or disadvantages, this methodology has given some interesting results indicating that leakages can be detected and isolated in some cases.

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