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A Global Approach for Detection of Leaks in Closed-Loop Water Distribution Networks

D. SALA and P. KOŁAKOWSKI

ABSTRACT

The problem of leak detection is important from the industrial (increasing cost of water distribution) and environmental (diminishing water resources) point of view. Researchers representing various disciplines are involved in both theoretical and practical aspects of the problem trying to give it a holistic treatment, which should eventually lead to an implementation in the field.

This paper deals with an interdisciplinary transfer of ideas from structural mechanics to hydraulic engineering using analogies between truss structures and water distribution networks and the graph representation of both systems. The problem of hydraulic system modelling and leakage identification was formulated and solved at steady-state flow within the framework of the Virtual Distortion Method (VDM) – a method of fast reanalysis.

INTRODUCTION

This work is an attempt to transfer the ideas derived from the structural mechanics to hydraulic engineering using analogies between truss structures and water distribution networks and the graph representation of both systems. The problem of hydraulic system modelling and leakage identification was formulated and solved at steady-state flow within the framework of the Virtual Distortion Method (VDM) – a method of fast reanalysis.

This paper is a continuation of the research reported in [1]. The previously developed approach has been extended to take into account:

Damian Sala, Smart-Tech Centre, Institute of Fundamental Technological Research, Polish Academy of Sciences, Pawińskiego 5B 02-106 Warsaw, Poland, e-mail: dsala@ippt.gov.pl, web: http://smart.ippt.gov.pl

Przemysław Kołakowski, Adaptronica sp. z o.o., R&D company, Szpitalna 32, 05-092 Łomianki, Poland, e-mail: pkolak@adaptronica.pl, web: http://www.adaptronica.pl

- precise location of leakage along network's branch (not just the midpoint) - this has been achieved by modifying the leakage-sensitive influence matrix in an iterative way
- the possibility of locating the pressure sensors in an arbitrary place in the network - this is of practical importance as sensors could be mounted in points of easy access e.g. hydrants

The extended approach for detection of leaks in water distribution networks using the VDM is a patent-pending application [2] submitted to the Polish Patent Office in 2010.

Numerical example of a simple water distribution network demonstrates new capabilities of the proposed approach. Lab-scale and large-scale experiments for water networks in continuous operation are envisaged**.**

ANALOGIES BETWEEN MECHANICS AND HYDRAULICS

The analogies between mechanical and hydraulic systems were presented by Hardy Cross. In his work [3], similarities between truss structures in structural engineering and closed-loop water distribution networks in hydraulics were described.

The most important observation is that both the systems can be mathematically modeled by a graph. If so, two basic rules can be applied resulting from Kirchhoff's laws for electrical circuits i.e. the equilibrium at nodes and the conservation of energy (continuity of flow or deformation) in closed loops of the graph. The difference between mechanics and hydraulics is that water distribution networks have to be modeled by an oriented graph, showing the direction of water flow. Another major difference is that the constitutive law in hydraulics is non-linear in contrast to the commonly used linear Hooke's law in structural mechanics.

FORMULATION OF THE LEAK PROBLEM

The Virtual Distortion Method (VDM) presented in [4] is the basis of analytical formulation of the leak identification problem. Referring to the system analogies described briefly in previous section, the relation between water head h (equivalent of displacements) and head loss Δh (equivalent of strains) can be written as follows:

$$\Delta h = N^T h \tag{1}$$

where N is a constant matrix (storing only three values 0, 1, -1) connecting branches to nodes and showing the direction of flow in the network. The 1 (flow coming out) and -1 (flow coming in) entries are incident to the direction of flow, therefore the matrix N is called incidence matrix.

The global equilibrium is ascertained by the formula combining external supply q (equivalent of external forces) and internal flow Q (equivalent of internal forces):

$$q = NQ \tag{2}$$

The Hazen-Williams constitutive law, for calculating head loss Δh, reads:

$$\Delta h = RQ^{1.85} \tag{3}$$

and for calculating internal flow Q, reads:

$$g\Delta h^{0.54} = Q \tag{4}$$

where R is the hydraulic resistance and g – hydraulic conductance, respectively. For the sake of making use of the Virtual Distortion Method, the non-linear system of a water distribution network has to be linearized, by taking a tangent conductance g' for every branch (cf. [5]) instead of the original g:

$$g' = \frac{dQ}{d\Delta h} = 0.54 g\Delta h^{-0.46} \tag{5}$$

Taking into account the connectivities of branches and aggregating equations for the whole network, we get a linearized system of equations to be solved for water head h at the defined supply q:

$$G'h = q \tag{6}$$

where G' is a matrix combining tangent conductances g'.

In the framework of the VDM, some pseudo-quantities (called virtual distortions) are introduced to the system in order to modify it according to user's intention (direct problem e.g. change of element cross-section) or to identify an existing modification (inverse problem e.g. detection of defect). To fully take advantage of the VDM, the influence matrix D needs to be built. This matrix stores information how the entire system responds to some prescribed virtual distortions. In order to model leaks in the network, the virtual distortions are imposed in the form of two flow vectors directed towards the midpoint of a branch (see Fig. 1). The corresponding influence matrix D has *n* rows and *b* columns where *n* is the number of nodes, *b* – number of branches in the network.

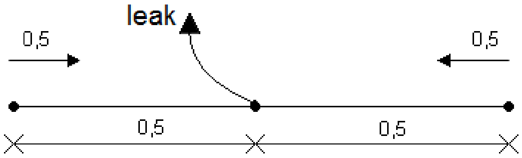

Figure 1. Flow vectors pointing towards the midpoint of a branch to simulate leak.

The problem of leak detection is formulated as minimization of mean difference between the measured h^m and modeled h water head at pressure sensors:

$$\min \Sigma_{sensor} (h - h^m)^2 \tag{7}$$

The modeled water head h is a sum of the initial value h^{ini} and the correction h^{cor}, which can be expressed in terms of the influence matrix D and pseudo water heads Δh^0 (virtual distortions - design variables):

$$h = h^{ini} + h^{cor} = h^{ini} + D\Delta h^0 \tag{8}$$

Proper constraints should be imposed to complement the optimization problem. Water head must not be negative at positive supply:

$$h \geq 0 \tag{9}$$

At the assumed direction of flow vectors in Fig. 1 when building the influence matrix, the resultant virtual distortions must not be positive:

$$\Delta h^0 \le 0 \tag{10}$$

The optimization task (7), (9), (10) is the quadratic programming problem, which can be solved by standard routines.

PRECISE DETECTION OF LEAK ALONG BRANCH

The previously developed approach [1] took the simplifying assumption that leak is modeled by inserting an extra node in the middle of the branch. The identification of leak was limited to pointing out the branch in which the leak occurred.

It is obvious however that branches of water distribution systems may be quite long. Therefore there is a need to track exact positions of leakage along the branch instead of identifying just the branch. In order to resolve the problem one should change the way of building the influence matrix from two fixed flows (of the same magnitude) shown in Fig. 1 to two varying flows (of different magnitude) depicted in Fig. 2.

Let us consider an example of the water distribution network consisting of 6 nodes, 9 branches and 4 loops, presented in Fig. 3. The process of searching for leakage along a branch proceeds in iterations. It starts with the assumption that the leak is located in the middle of the branch.

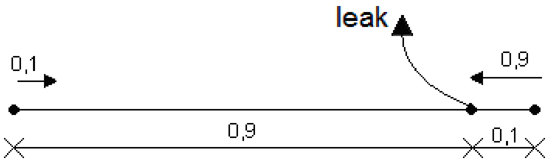

Figure 2. Flow vectors pointing towards arbitrary point of a branch to simulate leak.

If this assumption is not met i.e. the position of leakage is arbitrary, the result of leak identification using the standard procedure will be diffused to the network branches connected to the node which lies the closest to the leakage (see Fig. 4). This tells us that we should focus our attention on just halves of the branches suspected of leakage, which are adjacent to the previously determined node. If so, a correction for building influence vectors for virtual distortions imposed in these co-nodal branches should be applied. This is done by subsequent halving of the analyzed branches to pinpoint the precise position of leak with a defined accuracy. The outcome of this iterative process is shown in Fig. 4.

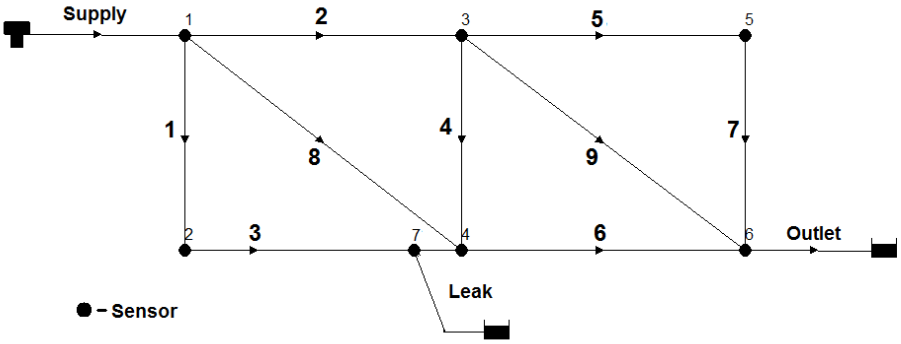

Figure 3. Four-loop water network: leak in arbitrary position.

Multiple leak locations can be handled by the proposed method of precise leak positioning as well. A result for the 4-loop network exposed to three leaks (see Fig. 5) is presented in Fig. 6.

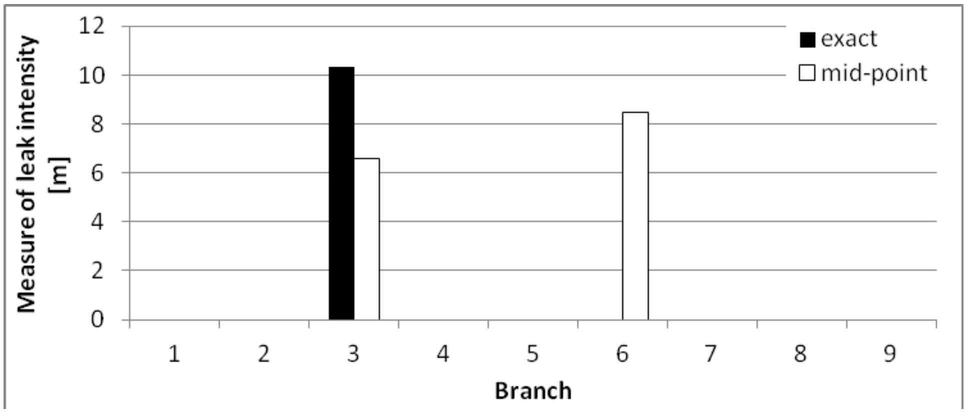

Figure 4. Performance of old algorithm with leak prescribed to midpoint of a branch vs. new algorithm pinpointing the exact leak position, for the case shown in Fig. 3.

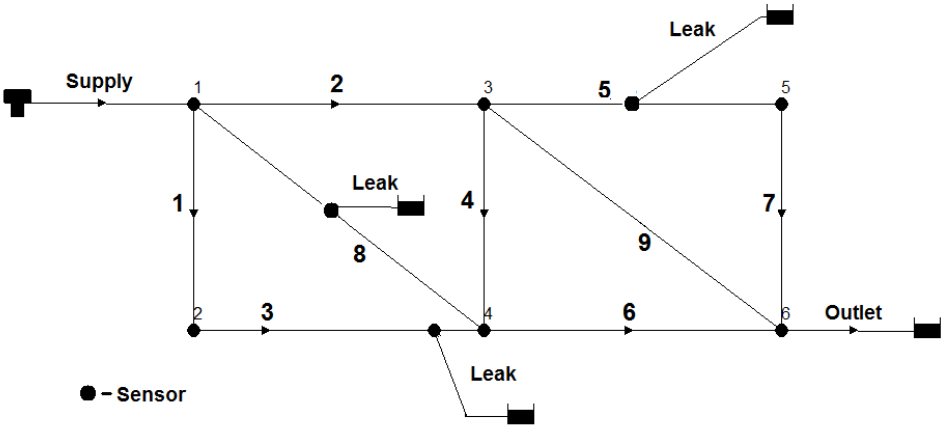

Figure 5. Water network exposed to three leaks.

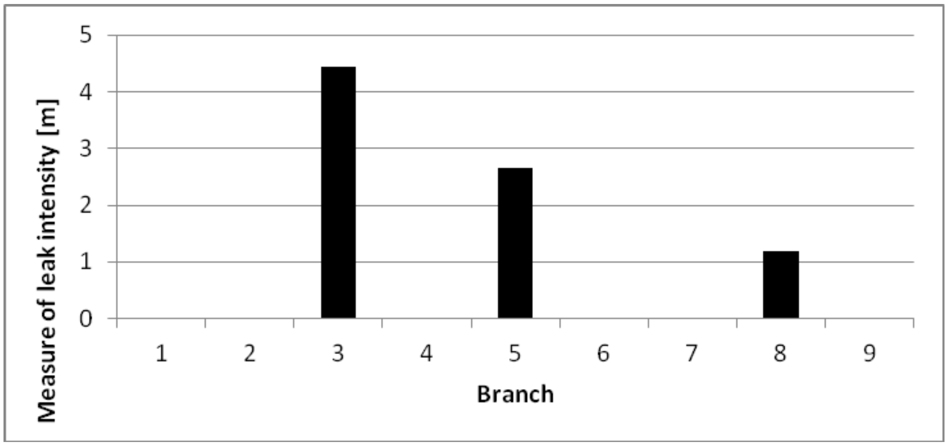

Figure 6. Result of identification for three leak locations (cf. Fig. 5).

MEASURING PRESSURE AT ARBITRARY POINTS

Measuring water head values at network nodes was another limitation of the first approach [1]. This assumption is very impractical as network nodes are usually not good candidates for taking measurements. It is much more convenient to measure at arbitrarily located hydrants with the help of suited sensors. From the point of view of VDM, the operation requires rearrangement of the influence matrix from being rectangular n x b to being quadratic b x b, with the assumption that every branch is equipped with one hydrant.

A distribution of hydrants is proposed for the analyzed network (see Fig. 7) in order to check the usefulness of hydrant measurements for the leak detection. The result for the case of leakage located in the middle of branch no. 9 is presented in Fig. 8 and confronted with nodal measurements. The agreement is very good which confirms that the points of measurements have no impact on the physics of the problem.

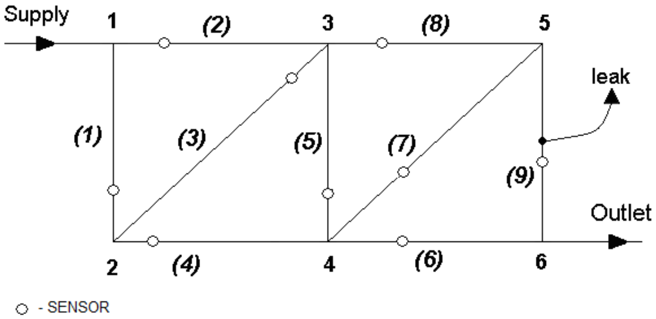

Figure 7. Water network with sensors placed in hydrants.

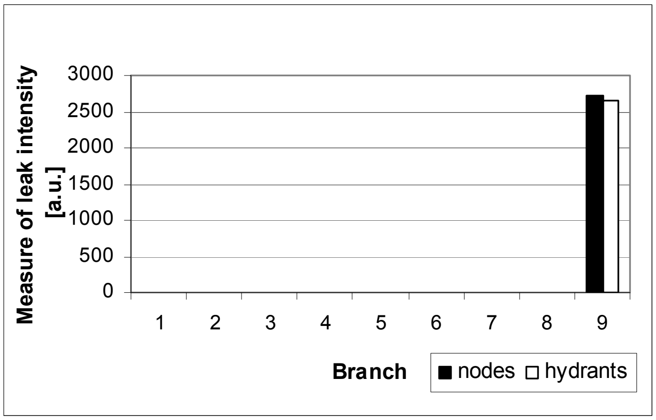

Figure 8. Comparison of leak identification with sensors placed at nodes and hydrants.

ACCOUNT FOR NON-LINEAR CONSTITUTIVE LAW

The constitutive law in hydraulics is of the form (3)-(4). Using the VDM which is in principle suited to solve linear problems, we can take non-linearities into account e.g. by approximating a curve with bi-linear characteristics and compensating the transition from one section to the other by introducing virtual distortions. This is how plasticity in mechanics can be modeled.

Another approach, which can be successfully used in hydraulics, is to perform linearization of the whole system making use of tangent hydraulic conductances (5). Such linearization enables to compare VDM-based results with the EPANET software [6] for the 4-loop network with one leak. One of such graphs is shown in Fig. 9.

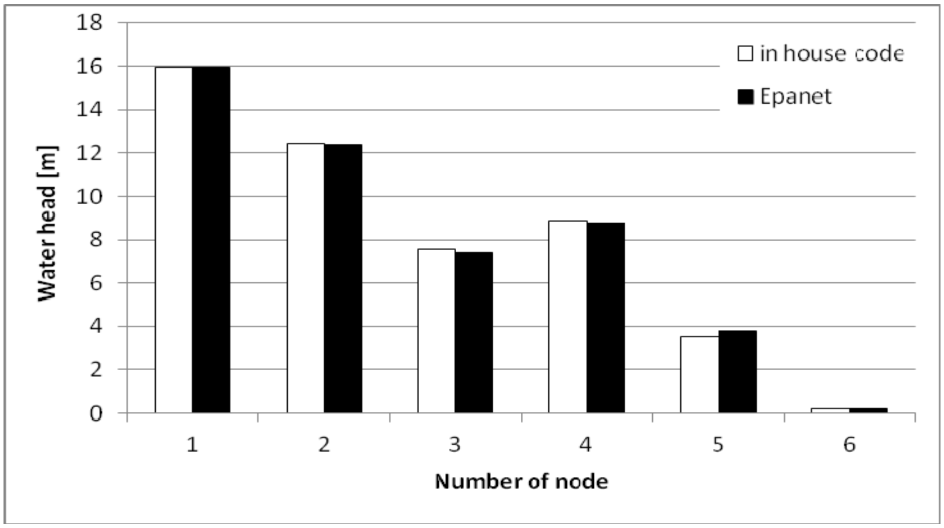

Figure 9. Comparison between in-house code (linearized law) and EPANET software (non-linear law) for the 4-loop network with one leak.

INFLUENCE OF DATA NOISE ON IDENTIFICATION RESULTS

Another problem considered in the paper was an introduction of some random noise to the input data. The target was to check whether the leak identification algorithm is still able to find the proper solution for noisy data. Results of this test are presented in Fig. 10. We can see that the algorithm is quite sensitive to the noise in input data. The identification result for the 10% noise level becomes ambiguous.

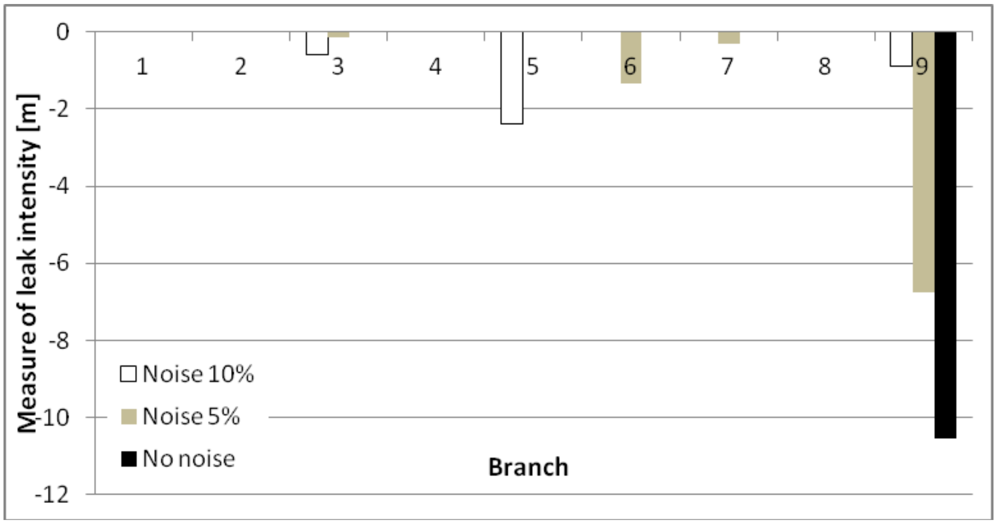

Figure 10. Comparison of leak detection with different levels of noise in input data.

CONCLUSIONS

The paper presents an adaptation of the VDM-related identification problems in structural mechanics (cf. [7], [8]) for the leak detection problem in water distribution networks operating at steady state flows. Three significant improvements have been made. First, the problem has been formulated for the Hazen-Williams constitutive law, which was subsequently linearized. Second, the ability of the leak identification algorithm to track the position of leak precisely along network branch was added. Third, practical aspect of the problem i.e. taking measurements of water head levels at hydrants instead of nodes was considered. These solutions are possible thanks to appropriate modifications of the influence matrix. The comparison of VDM-based and EPANET results is very good. The influence of noise in input data may cause diffusion of the leak identification results, thus accurate pressure sensors are required in field measurements. Further research will be focused on extension of the approach for varying-in-time analysis.

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