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Leak detection and monitoring in hydraulic networks

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Abstract

Managing water distribution systems includes detection of leaks to improve the effectiveness of the service. The section of a hydraulic network where a leak occurs can be detected if the SCADA SYSTEM is coupled to a software based on the Method of Characteristics (MOC), which is, presently, the best one to simulate steady and unsteady flows, as shown by illustrative examples in this paper. The paper shows the basic equations and describes the basis of the computer program and corresponding network topology description that provide the engineer with the easiest way to simulate network operation. The use of MOC, for both steady and unsteady flow monitoring, facilitates the network calibration in order to reduce the sensitivity of the data errors due to inaccuracy in the value of friction factors.

1 Introduction: The problem of operational control

The purpose of a water distribution network is to supply the consumer systems (domestic, commercial and industrial) with water of an adequate physico-chemical quality, conforming to the pressure levels stipulated in current standards.

The network is subjected to continuous variations of the demand and also to instantaneous accidental variations caused by problems such as fires. Exceptionally, when there is a burst in a pipe of the network, there is a marked increase of the demand, with a consequent variation of the nodal heads that may cause supply problems if the network is not adequately designed and monitored.

In the network design, the continuous demand variations are analyzed and, in this opportunity, the dimensional characteristics are predicted for the pipes, valves, pumps and sector tanks, to ensure the supply with adequate quality, optimizing the investments. The pumps operate in order to increase the pressures during peak demand hours, the control valves control the nodal pressures in the network sectors, where usually, it is more economical to install regulating tanks to take care of the hourly consumption variations in the sectors.

The typical network of Figure 1 shows a configuration with several elements (ENO's) and NODES, to which not more than a non-pipe ENO is connected. The network has 27 ENO's and 23 NODES and was originally designed to supply the factory F1 with flow control at valve 15, and to supply the sector distribution networks S1, S2 and S3 by gravity. Later, the network was enlarged to supply sectors S4, S5 and S6 by pumping; the speed control of pumps 21 has the objective of mantaining an adequate pressure at NODE 17.

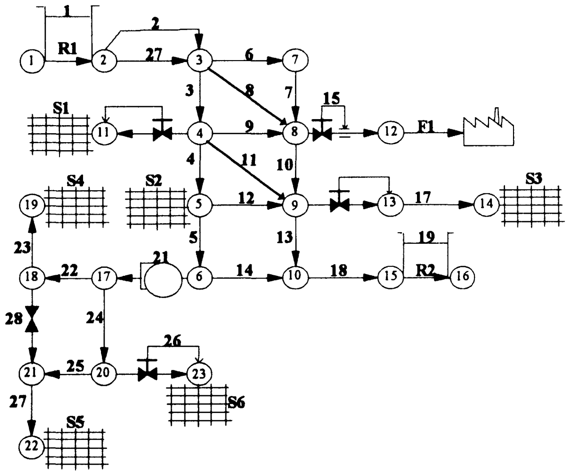

Figure 1: Typical transmission network

Tank R2 is a downstream tank, that is to say, it receives water during off-peak demand periods and supplies stored water during peak demand periods. Valves 20, 16 and 26 control the pressures in networks S1, S3 and S6 and shut-off valve 28 makes possible to interconnect NODES 18 and 21 in case of accidents (bursts) in one of the pipes 22 or 25 in order to ensure the supply of networks S4 and S5.

The example characterizes real situations found in urban water supply systems, where enlargements are made in existing networks in order to follow population growth, with the installation of automatic control valves (ACV) for pressure (or flow) regulation to meet the sector demand variations

The problem that presents itself is a double one. First, one must **optimize the operation,** that is to say, to ensure that, through the control of nodal pressures, the demands are satisfied according to the specifications, with the minimum consumption of energy and using the stock of water that are available in the sector tanks. Secondly, one must monitor the operation in order to check the possible occurrence of leaks (or bursts) that may jeopardize the supply and, once the leak is detected, to find out its location in order to repair it. These two objectives may be united and defined as the problem of **Operational Control.**

This paper purports to present the general equations and the calculation algorithm based on the Method of Characteristics that enable the analytical

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solution of the problem of Operational Control, and to discuss the problem based on the results obtained in real time processing.

2 Topological model and equations

The network is made up of elements (ENOS): pipes, tanks, pumps, valves, etc; and NODES, with or without point demand, to which not more than one non-pipe ENO is connected. Establishing an arbitrary positive sense in the ENOS, designating the upstream NODES as N1 and the downstream ones, N2 and adopting for the ENOS a code T that identifies them as pipe, valve, pump or tank and with a sequential code I that identifies them in the installation, each ENO may be represented by vectors of the type (I, T, N1, N2). Thus, in figure 1, if the code T=3 is used for pump, the ENO 21 is written as (26, 3, 6, 17) and, with a code T=2 for tanks, the three tanks in the network are identified as (1, 2, 1, 2), (17, 2, 13, 14) and (19, 2, 15, 16). The set of vectors characterizes the topology of the network and enables it is reconstructed by identifying all the elements [1, 2, 3].

In hydraulic networks the transmission of information in a pipe ENO is obtained by the change of head (H) and of flow (Q) at each point P. At each instant t they are functions of the known values of head and flow at positions A and B at the previous calculation instant, points (t -Δt) according to the equations obtained from the method of characteristics.

$$H_P = H_A - B(Q_P - Q_A) - RQ_P|Q_A| \tag{1}$$

$$H_P = H_B + B(Q_P - Q_B) + RQ_P|Q_B| \tag{2}$$

where B is the impedance term and R the resistance of the pipe:

$$B = \frac{a}{gA} \qquad R = \frac{f\Delta x}{2gDA^2} \tag{3a,b}$$

where a is the celerity (velocity at which the information is transmitted), D is the pipe diameter, A the pipe cross-sectional area, f is the friction factor of the universal formula for head-loss (these values together represent the properties of the pipe) and g the acceleration of gravity.

Alternatively, it is numerically advantageous to obtain the same values Hp and Qp calculating previously the information transmitted from points A, B and C to points L (left) and R (right) and afterwards to point P, as schematically shown in Figure 2 [3].

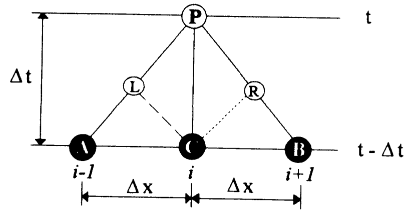

Figure 2:- Calculation grid

$$Q_P = (C_L - C_R)/(B_L + B_R) \quad (4) \qquad H_P = C_L - B_L Q_P = C_R + B_R Q_P \quad (5)$$

where,
$$C_{L,R} = H_{A,B} \pm B Q_{A,B} \mp \frac{R}{2} Q_{L,R} |Q_{A,B}| \quad (6)$$

$$B_{L,R} = B + \frac{R}{2} |Q_{L,R}| \quad (7)$$

with,
$$Q_{L,R} = \pm \frac{(H_{A,B} - H_C) \pm B(Q_{A,B} - Q_C)}{2B + \frac{R}{2}(|Q_{A,B}| + |Q_C|)} \quad (8)$$

The transmission of information through the network passes through NODES, generically represented in figure 5, in which MC is the number of pipes that "converge" on the NODE and MD is the number of pipes that "diverge" from the NODE. At a given NODE, it is possible that there is a demand D(t) and a flow Q_{PE} of a non-pipe ENO associated to the given NODE.

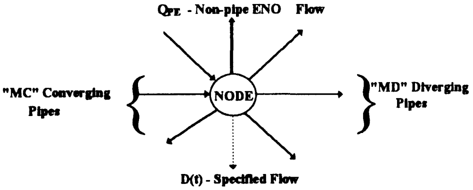

Figure 3: Scheme of a generic NODE

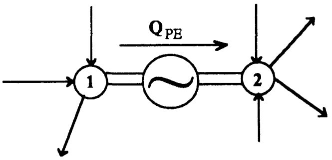

Figure 4: Scheme of non-pipe ENO

From the consideration of continuity at the NODE, it is easy to arrive at the equation called NODE equation [3].

$$\boxed{Q_{PE} = E_N - B_N H_P} \quad (9)$$

where:

$$E_N = \sum_{j=1}^{MC} \frac{C_L(j)}{B_L(j)} + \sum_{k=1}^{MD} \frac{C_R(k)}{B_R(k)} \quad (10) \qquad B_N = \sum_{j=1}^{MC} \frac{1}{B_L(j)} + \sum_{k=1}^{MD} \frac{1}{B_R(k)} \quad (11)$$

are calculated from previously known values at the previous instant (t - Δt) and H_P is the unknown head at the NODE.

A non-pipe ENO, such as a pump, valve, etc. in a network has an upstream NODE (1) and a downstream NODE (2), as shown in figure 4. In the case of an ENO that does not accumulate mass, the head difference, $H_{PE} = H_{P1} - H_{P2}$ is:

$$\boxed{H_{PE} = E_E - B_E Q_{PE}} \quad (12)$$

where
$$E_E = \frac{E_{N1}}{B_{N1}} - \frac{E_{N2}}{B_{N2}} \quad e \quad B_E = \frac{1}{B_{N1}} - \frac{1}{B_{N2}} \quad (13)$$

Equation 12 is the equation of compatibility of the non-pipe ENO. The unknown values E_N and B_N characterize the dynamic effect transmitted through the network by the non-pipe ENO and depend only upon the status of the network at a previous calculation step. The non-pipe ENOS receive information from the network (E_E, B_E), transmitted by the equation 12. They process this

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information accordingly to its characteristics represented by the equation of the non-pipe ENO, that includes all the parameters that are connected by the following relationship:

$$H_{PE} = H_{P1} - H_{P2} = \varphi(Q_{PE}) \tag{14}$$

The combination of the transmitted and processed information results in the modified equation:

$$F(Q_{PE}) = \varphi(Q_{PE}) + B_E Q_{PE} - E_E = 0 \tag{15}$$

that is retransmitted to the network as a new value of Q_{PE}. The nodal heads H_{P1} and H_{P2} are obtained from equation 9, through the flows transmitted to the pipes.

For a generic non-pipe ENO that does not accumulate mass, represented in Figure 4, the particular equation φ (Q_{PE}) is known and may be substituted in equation 15, resulting in the case of a mass accumulating tank and we have:

$$Q_{PE}|Q_{PE}| + FQ_{PE} + G = 0 \tag{16}$$

where the values of F and G are determined for each calculation instant for each one of the non-pipe elements. The solution of equation 16 may be obtained as [3]:

$$Q_{PE} = \frac{2G}{F + \sqrt{F^2 + 4|G|}} \tag{17}$$

For the pressure or flow control valves, the values of the pressure (H_{P1} or H_{P2}) and of the flow (Q_{PE}) are stipulated and the other variables are calculated as shown in Ref. 4.

$$Q_{PE1} - Q_{PE2} = Q_R = (E_{N1} + E_{N2}) - (B_{N1} + B_{N2})H_R \tag{18}$$

where H_R is the tank level (given), and a corresponding flow Q_R is calculated that is transferred to (from) the tank from (to) the network.

If the purpose of the investigation is focused in steady flow, in extensive period or in leak monitoring, it is to be remembered that the impedance $B = a/gA$ is not important and it is possible to substitute the celerity by $a = L/\Delta t$, where L is the pipe length and the impedance is given by:

$$B = \frac{L}{gA\Delta t} \tag{19}$$

Following the suggestion of Shimada [5], the network pipes, of length L_i and friction factor f_i, may be substituted by equivalent pipes of equal length L_0 (usually 100 m) and a corresponding friction factor given by:

$$f_i^* = \frac{f_i L_i}{L_0} \tag{20}$$

This procedure accelerates the convergence of the calculation numerical procedure for the final steady flow. For transient and oscillatory states, the time interval is obtained from the equation:

$$\Delta t = L_i / na_i \tag{21}$$

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where n is an integer; for this, some adjustments in the value of celerity may be necessary and the limit of ±10% is recommended. This is preferable when compared to the processes of interpolation in order to avoid damping.

3 Compatibility conditions - The inverse problem

In a generic network with specified nodal demands, we may distinguish the N NODES, the T pipes and the R tanks with known levels and the NT non-pipe elements. We must determine the N - 2R nodal heads and the T + NT + R flows at the ENOS. Indeed, in order to satisfy the equation of continuity at the NODE (Equation 9), there result 2T flows at the extremities of the pipes.

However, if the network is monitored in transient state and the nodal heads (H_i^*) are obtained in real time through a data acquisition system (SCADA), the flows Q_{P1} and Q_{P2} result and, if they are different in a given pipe, the difference must be attributed to a leak, as shown in Figure 5. The leaks are thus detected in the solution of the inverse problem during the acquisition of data in transient state.

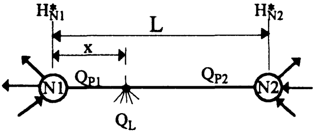


Figure 5: Pipe with a leak

$$Q_L = Q_{P1} - Q_{P2} \qquad \text{(leak)} \tag{22}$$

Writing the equations in this way allows the solution of the inverse problem without difficulties using the algorithm proposed in Ref. 6, in which the known nodal heads H_i * are used for the calculation of E_N and B_N and the flows are calculated through Equations 5 with $H_p = E_N / B_N$. The calculation procedure is progressive in time until convergence is obtained with $H_P \rightarrow H^*$. Adjusting the demand D(t) to simulate the nodal leak and (or) obtaining the leak in the pipe by the difference between the flows at the extremities (see Figure 5), one obtains convergence in the calculation procedure, satisfying the continuity at the NODES and conforming to the monitored heads H*.

How many and which NODES of the network should be monitored and which is the topological condition that must be obeyed in order to arrive at a unique solution? Ligget [7] proposes the definition of a merit factor (MEF) calculated in terms of successive measurements of the heads H* at the network NODES, confronted with the values of the calculated H_i calculated in function of the instantaneous boundary conditions.

$$MEF = \sum_{i=1}^{M} (H_i^* - H_i)^2 \tag{23}$$

The minimum value of MEF defines the nodal location of the leak! The proposed process is extremely complex, matricial and will hardly be generalized to complex networks such as the presented in Figure 1, with several non-pipe ENOS. The process suggested here is more effective and allows to use the same criterion for the nodal location of the leak, through successive measurements of the heads.

The remaining unsolved problem is the obtention of the answer to the question of uniqueness of the solution for the cases in which the nodal heads H_i * are stabilized, partially monitored with the network presenting leaks that must be correctly located analytically.

The example of Figure 6 with pipes 500 m long, 300 mm diameter and C = 100 (Hazen-Williams) is solved by the proposed method for locating a leak at NODES 3 and 9 monitoring the heads at all the NODES and also without monitoring the heads at NODES 3, 7 and 11 (case A). However, if we do not monitor adequately NODE 9, leaks are detected at NODES 2, 6, 8 and 10 for the same nodal heads (Case B)! The analysis of the results allows to evaluate the possibilities of obtaining (or not) the unique solution for the above stated problem of network monitoring. It must be noted that in the network of Figure 7 we have N = 15, R = 3, NT = 0, NX = 9 (NODES 2, 3, 4, 6, 7, 8, 9, 10, 11) and T =14, resulting in NT = NI = 40 and the network is uniquely determined in the solution of the direct problem, that is to say, the nodal heads and the flow in the pipes are calculated, obeying to the personality of the network [6].

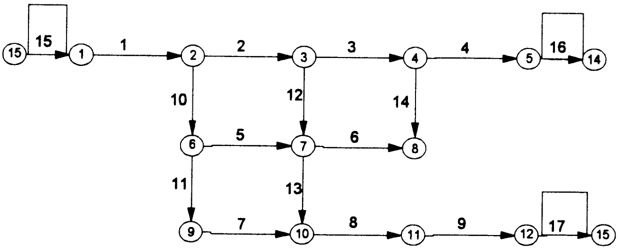


Figure 6: Detection of leaks at NODES 3 and 9

For the inverse problem, when more than three of the nine internal NODES are not monitored, distinct solutions for the leaks are obtained, as shown in Table 1. It should be observed that the total leakage in the network is the same, but entirely different in position and values from cases A and B.

It is important to note that small differences in the heads result in completely different solutions, independently from the number of monitored NODES, as may be seen in the comparison of the values of corresponding heads shown in Table 1.

Table 2 shows the corresponding flows in the pipes of the network for cases A and B, in correspondence with the values of Table 1.
Though the values of flow are not very different (as well as the values of head), the leaks detected are entirely different, showing that the solution in steady state will always be doubtful. Indeed, if all the monitored heads were considered as the values of Table 1, with small differences of head for cases A and B, the

leaks that would be obtained would be entirely different. It would be necessary to establish a calculation in transient state for successive instants of leak detection in the network NODES, for the influence of the precision in data acquisition is notorious, as may be perceived examining presented in Table 1 and 2, even for significant leaks in the network. It must be noted that the leak of 30 l/s corresponds to 17,6% of the total consumption of 170.8 l/s!

	A		B		ΔH_N
NODE	H_N (m)	Q_L (l/s)	H_N (m)	Q_L (l/s)	$H_N(A)-H_N(B)$
1	100		100		
2	85.9354		85.9354	2.22	
3	82.1359	10.0	82.3197		-0.1838
4	82.2538		81.2538	4.12	
5	80		80		
6	81.9416		81.9416	9.92	
7	81.3510		81.3805		-0.0295
8	81.3024		81.3024	2.34	
9	80.1752	20.0	80.6709		-0.4957
10	79.3999		79.3999	11.40	
11	74.7000		74.6999		
12	70		70		-0.0001
13	100		100		
14	80		80		
15	70		70		
No monitoring NODES 3, 7 e 11		Total 30 l/s	No monit. 3,7,9,11	Total 30 l/s	

Table 1: Nodal Heads and leak (flows)

	FLOW (l/s)		
PIPE	CASE A	CASE B	$\Delta Q = Q_A - Q_B$
1	170.8	170.8	0
2	84.3	82.0	2.3
3	38.3	42.4	-4.1
4	46.3	46.1	0
5	30.8	30.0	0.8
6	8.0	10.3	-2.3
7	35.7	46.6	-10.9
8	94.5	94.5	0
9	94.5	94.5	0
10	86.6	86.6	0
11	55.7	46.6	9.1
12	36.0	39.6	-3.6
13	58.8	59.3	-0.5
14	-8.0	-8.0	0

Table 2: Flows in the pipes

The illustrative example of the simple network of Figure 6 points out some factors:

a) The proposed method is effective for the determination of the personality of the network both in the case of the direct problem as in the case of the inverse problem (monitored heads).

b) Even if it is possible to demonstrate the uniqueness of the solution of the inverse problem, with monitoring of all the heads, the precision of the physical data of the network and of the data acquired in real time (SCADA) are important and difficult to attain in practice to such a degree that it may be possible to guarantee that the analytical solution coincides with the real solution.

c) Apparently, short of deeper research, the analytical definition of the uniqueness and of the type of NODES to be monitored in order to obtain a unique solution in the detection of leaks is improbable for gridiron networks.

4 Location of leaks in pipes

The calculation procedure proposed in transient state, with monitoring of the heads in all the nodes, allows the solution of the inverse problem and to determine the personality of the network [6]. The instantaneous flows at the upstream and downstream extremities of each pipe are obtained and therefore, through Equation 22 the leak (Q_L) is determined as shown on figure 5. With the value of the monitored heads and of the calculated flows Q_{P1} and Q_{P2}, we obtain the location of the leak through the expression:

$$x = \frac{(H_1^* - H_2^*) - \dfrac{f_2 L Q_{P2}^2}{2gDA^2}}{\dfrac{f_1 Q_{P1}^2}{2gDA^2} - \dfrac{f_2 Q_{P2}^2}{2gDA^2}} \qquad (24)$$

that corresponds to a leak located in the pipe of the network operating in "quasi-static" state.

It must be noted that Equations 1 and 2 associated to MOC (Method of Characteristics) represent the phenomenon of propagation of information through the pipes of the network and are valid along the characteristic straight lines represented in Figure 2. From Equations 1 and 2 it may be seen that Q_{P1} and Q_{P2} tend to be equal in the pipe, with the progressive processing. Therefore, the unbalancing of the flows will be always nodal:

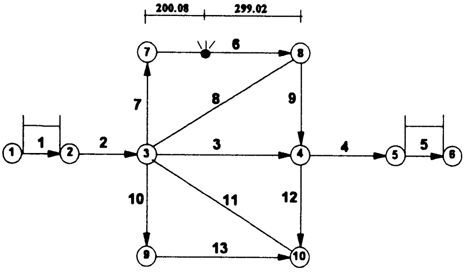
$$Q_{LN} = E_N - E_N^* \qquad (25)$$

where

$$E_N^* = H^* B_N \qquad (26)$$

The proposed method makes possible the instantaneous calculation of flows Q_{P1} and Q_{P2} at the upstream and downstream extremities of each pipe, satisfying the continuity conditions at the NODES of the network, make possible to locate leaks in the pipes.

The following example (Fig. 7) illustrates the statements above and clarifies the proposed method, for a simple situation, where a leak was detected from the heads monitored in the network. In the example, all the pipes are 500 m long, diameter of 400 mm and C = 100. the values of the nodal differences are presented in the Table of the figure.



NODE	EN	BN	HN	EN-BN*HN
3	20.66	0.23	90.44	0.0000
4	11.23	0.13	88.97	0.0000
7	8.22	0.09	90.18	0.0057
8	11.14	0.12	89.99	0.0043
9	8.32	0.09	90.24	0.0000
10	11.15	0.12	90.03	0.0000
			Σ	0.0100
	QP1 = 0.042			
	QP2 = 0.032			
	QL = QP1-QP2 = 0.01			

Figure 7: Illustrative example - Leak value determined from monitored heads

5 Conclusions and recommendations

The method proposed in this paper for the detection of nodal leaks is, as shown, more objective than the methods currently available (see Ref. 7 for instance). The solution of the inverse problem, of locating leaks in intermediate sections, is not unique and it is necessary to define conditions for the uniqueness of the solution. This solution is unique in the case of simple systems, with continuous monitoring of pressures and analysis of the temporal histograms of the pressures but, for networks, unresolved problems arise that were presented in this paper and for which it is recommended that research be intensified.

Acknowledgements

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