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# Decision on Leakage of Heat-supply Pipe Network Based on Multi-sensor Information Merge

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**Abstract:** The complicated structure of heat-supply pipe network leads to the issue that the leakage position is difficult to locate by a single sensor. We propose to exploit the merge information by multi-sensor to determine the leakage pipeline section. The mathematical model is first established according to the topology of the pipe network. Furthermore, We present the concept of leakage time difference vector group and assign the elementary probability according to the cosine of the intersection angle between the given time difference vector group and the real measured time difference vector group. Experimental results show that the proposed scheme realizes the diagnosis of the leakage pipeline section in the complicated heat-supply pipe network.

**Key words:** Evidence theory, pipeline section decision, heat-supply pipe network, information merge

## INTRODUCTION

Heat-supply pipe network is a large system to distribute heat to house and industry. The network is installed under-ground and entangled complicatedly. Therefore, it is difficult to locate the leakage position. Also, since the number of sensors of the pipe is limited, accurate locating leakage is hardly possible. On the other hand, when locating leakage is delayed, economical and social losses become bigger. Thus, the locating leakage techniques are required to minimize the massive loss when the leakage occurs.

For the problem of locating the leakage position in the pipe network, the common used method is to assign the whole pipe network to the different measurement regions and there is an apparent fixed border between each region which is connected by control valve, which is closed usually. The flow sensors are installed on the border to detect and analyze the flow data, realizing the leakage detection and location (Zheng *et al*., 2003; Bimpas *et al.,* 2010; Abhulimen and Susu, 2004). Lei *et al.* exploits a space-based simulation model to investigate the leak detection strategy of a heating network (Lei and Zou, 2010). They established a leakage diagnosis system based on the back propagation neural network. Yang *et al.* analyzed the generating mechanism and detecting principle of pipeline leakage sound wave as well as the frequency and attenuation characteristics of pipeline leakage acoustic signal (Yang *et al*., 2011). Iyeswariya *et al.* apply wireless sensor networks for leakage detection in underground water pipes to overcome the problem of water dispersion (Iyeswariya *et al*., 2012).

However, the schemes mentioned above need to establish the flow model of the pipe network, which is realized complicatedly. Therefore, we proposed a novel locating scheme, which does not need to establish the flow model, We exploit the merge information provided by multi-sensor and achieve the decision of the leakage of the pipe network.

## MULTI-SENSOR INFORMATION MERGE

Information merge can be classified into data level, feature level and decision level according to the level of the data abstracted in the information merge system. Decision level information merge makes the decision according to each sensor first and then merges the information for local decision by merge centre, which is depicted by Fig. 1. It is the highest level merge and its result will influence the decision level directly.

## MODELING OF THE TOPOLOGY OF HEAT-SUPPLY PIPE NETWORK

We exploit the adjacency matrix, incidence matrix and connection matrix to describe the topology of heat-supply pipe network, as shown in Fig. 2.

**Adjacency matrix:** Suppose G = (V, E) denote a directed graph matrix and $V = \{V_i|i = 1, 2, \ldots, n\}$, $E = \{E_i|i = 1, 2, \ldots, m\}$, where n represents the number of the nodes, m

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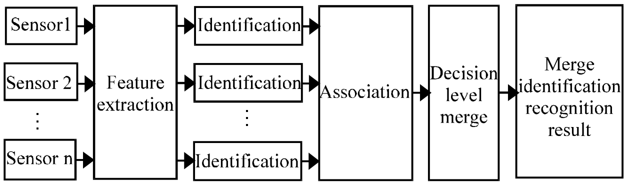

Fig. 1: Decision level merge

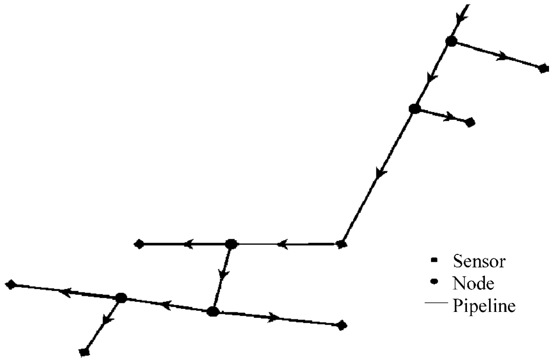

Fig. 2: Topology of directed pipe network

represents the number of edge. The adjacency matrix of G can be denoted by B (G) = ($b_{ij}$) with the order of n, where $b_{ij}$ represents the number of edge from $V_i$ to $V_j$ (Bimpas *et al*., 2010; Wei *et al*., 2006). The adjacency matrix can be expressed as:

$$B(G)=\left(b_{ij}\right)=\begin{bmatrix} 0&1&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&1&1&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&1&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&1&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&1&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix} \tag{1}$$

**Incidence matrix:** The incidence matrix of G can be denoted by N (G) = ($n_{ij}$) and:

$$n_{ij}=\begin{cases}1\\-1\\0\end{cases} \tag{2}$$

where, '1' represents $V_i$ is the start node of $E_j$, '-1' represents $V_j$ is the end node of $E_j$ and '0' represents $V_i$ is unassociated with $E_j$.

The incidence matrix in Fig. 2 can be expressed as:

$$N(G)=\left(n_{ij}\right)=\begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0\\ -1&1&1&0&0&0&0&0&0&0&0&0\\ 0&-1&0&0&0&0&0&0&0&0&0&0\\ 0&0&-1&1&1&0&0&0&0&0&0&0\\ 0&0&0&-1&0&0&0&0&0&0&0&0\\ 0&0&0&0&-1&1&0&0&0&0&0&0\\ 0&0&0&0&0&-1&1&1&0&0&0&0\\ 0&0&0&0&0&0&-1&0&0&0&0&0\\ 0&0&0&0&0&0&0&-1&1&1&0&0\\ 0&0&0&0&0&0&0&0&-1&0&0&0\\ 0&0&0&0&0&0&0&0&0&-1&1&1\\ 0&0&0&0&0&0&0&0&0&0&-1&0\\ 0&0&0&0&0&0&0&0&0&0&0&-1 \end{bmatrix} \tag{3}$$

**Connection matrix:** The connection matrix of G can be denoted by P (G) = ($P_{ij}$):

$$P(G)=\begin{cases}1\\0\end{cases} \tag{4}$$

where, '1' represents there is a route between $V_i$ and $V_j$ and '0' represents there is no route between $V_i$ and $V_j$.

The connection matrix in Fig. 2 can be expressed as:

$$P(G)=\left(p_{ij}\right)=\begin{bmatrix} 0&1&1&1&1&1&1&1&1&1&1&1&1\\ 0&0&1&1&1&1&1&1&1&1&1&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&1&1&1&1&1&1&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&1&1&1&1&1&1\\ 0&0&0&0&0&0&0&1&1&1&1&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&1&1&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix} \tag{5}$$

## DECISION ON LEAKAGE OF PIPELINE BASED ON EVIDENCE THEORY

**Fault detection based on intersection angle of vector:** The sensors in Figure 2 are distributed at $V_1$, $V_2$, $V_3$, $V_4$, $V_5$, $V_6$, $V_7$, $V_8$, $V_9$, $V_{10}$, $V_{11}$, $V_{12}$, $V_{13}$, suppose that the moment each

Table 1: Cosine of intersection angle of each vector

| $k_i$ | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ | $k_6$ | $k_7$ | $k_8$ | $k_9$ | $k_{10}$ | $k_{11}$ | $k_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cosine | 0.15 | 0.11 | 0.08 | 0.54 | 0.90 | 0.47 | 0.05 | 0.26 | 0.31 | 0.21 | 0.15 | 0.18 |

Table 2: Elementary probability

| | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_5$ | $m_6$ | $m_7$ | $m_8$ | $m_9$ | $m_{10}$ | $m_{11}$ | $m_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $E_1$ | 0.150 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_2$ | 0.077 | 0.110 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_3$ | 0.077 | 0.080 | 0.080 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_4$ | 0.077 | 0.080 | 0.084 | 0.540 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_5$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.900 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_6$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.470 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_2$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.050 | 0.067 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_8$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.260 | 0.063 | 0.072 | 0.077 | 0.075 |
| $E_9$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.310 | 0.072 | 0.077 | 0.075 |
| $E_{10}$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.210 | 0.077 | 0.075 |
| $E_{11}$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.150 | 0.075 |
| $E_{12}$ | 0.077 | 0.080 | 0.084 | 0.042 | 0.009 | 0.048 | 0.086 | 0.067 | 0.063 | 0.072 | 0.077 | 0.180 |

sensor receives the infrasound wave be $t_1$, $t_3$, $t_5$, $t_6$, $t_8$, $t_{10}$, $t_{12}$, $t1_3$ and $\Delta_{ti,\ j}$ represent the time difference between sensor i and sensor j. So, we know when leakage occurs at pipeline section $E_i$, the vector composed by time difference of its neighboring sensors is definite, that is:

When leakage occurs at pipeline section $E_1$, vector $T_t = [\Delta t_{3,5}, \Delta t_{5,6}]$ is definite.

When leakage occurs at pipeline section $E_2$, vector $T_2 = [\Delta t_{1,5}, \Delta t_{5,6}]$ is definite and so on.

During the real measurement, the moment each sensor receives the infrasound wave is $t_1'$, $t_3'$, $t_5'$, $t_6'$, $t_8'$, $t_{10}'$, $t_{12}'$, $t_{13}'$ and $\Delta_t'{}_{i,j}$ represents the time difference between sensor i and sensor j. So, we can calculate the time difference vector:

$$T_1' = \left[\Delta t_{3,5}', \Delta t_{5,6}'\right]$$
$$T_2' = \left[\Delta t_{1,5}', \Delta t_{5,6}'\right]$$

and so on.

The closer the distance between $T_i$ and $T'_i$ is, the bigger the probability of leakage occurring at pipeline section i is. As a result, we can make decision for pipeline section i by the cosine $k_i$ of the intersection angle between each group of time difference vector and $k_i$ can be calculated as follows:

$$k_i = \cos\langle T_i, T_i' \rangle = \frac{T_i \cdot T_i'}{|T_i||T_i'|} \tag{6}$$

When $k_i$ approaches 1, the possibility of leakage is bigger and when $k_i$ approaches 0, the possibility of leakage is smaller.

**Decision of pipeline section based on evidence theory:** The elementary probability function m on non-null frame Θ matches following:

$$\begin{cases} m(\phi)=0 \\ \sum\limits_{E \subseteq \Theta} m(E)=1 \end{cases} \tag{7}$$

where, E is the element and $E = \{E_i | i = 1, 2, \ldots, 10\}$.

According to the decision results by vector group above, we perform the decision merge by evidence theory (Paksoy and Gokturk, 2011; Liu *et al.*, 2009).

Suppose the frame $\Theta = \{E_1, E_2, E_3, E_4, E_5, E_6, E_7, E_8, E_9, E_{10}, E_{11}, E_{12}\}$, where $E_i$ denotes leakage occurs at the pipeline section i.

We determine the elementary probability function $m_i$ () according to $k_i$:

$$\begin{cases} m_i(E_i)=k_i \\ m_i(E_j)=\frac{1-k_i}{9} \end{cases} \tag{8}$$

where, i = 1, 2, ..., 10, j = 1, 2, ..., 10 and $j \neq i$.

The merge rule based on the evidence theory for function $m_1$, $m_2$, ..., $m_{10}$ in $\forall E \subseteq \Theta$ is as follows:

$$m(E)=\frac{1}{K}\sum_{E_1 \cap E_2 \cap \cdots \cap E_{10}=E_i}\prod_{1 \le j \le 10} m_j(E_i) \tag{9}$$

where, K is the normalized factor:

$$K=\sum_{E_1 \cap E_2 \cap \cdots \cap E_{10} \neq \phi}\prod_{1 \le j \le 10} m_j(E_i) \tag{10}$$

Finally, we can detect the fault pipeline section according to the merge results mentioned above.

**Experimental results:** The cosine of intersection angle of each vector is listed in Table 1. The elementary probability is listed in Table 2. The merge results are listed in Table 3. From the above table, we can see that the probability of leakage at pipeline section.

Table 3: Merge results

| $E_i$ | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ | $E_7$ | $E_8$ | $E_9$ | $E_{10}$ | $E_{11}$ | $E_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Probability | 0.014 | 0.010 | 0.012 | 0.042 | 0.723 | 0.072 | 0.004 | 0.028 | 0.036 | 0.021 | 0.014 | 0.018 |

Table 4: Degree of each node

| Node | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $V_5$ | $V_6$ | $V_7$ | $V_8$ | $V_9$ | $V_{10}$ | $V_{11}$ | $V_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d ($V_i$) | 1 | 3 | 1 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 3 | 1 |

$E_5$ reaches 72.3%, much higher than that at other pipeline sections. The proposed scheme decreases the uncertainty by data merge based on evidence theory.

## DISCUSSION ON END NODES AND LOCATING SENSOR

**Decision on end nodes of pipeline:** The location of leakage node usually is represented by the distance from the leakage point to the upper end node or the lower end node. Therefore, the serial number of the end node is very important. According to the discussion above, we know the leakage occurs at $E_5$. From the incidence matrix, we observe that the element '1' is located in the 4th column, which reveals the number of the start node is 4, that is, $V_4$. Furthermore, the element '-1' is located in the 6th column, which reveals the number of the end node is 6, that is, $V_6$.

**Decision on the locating sensor:** In the real heat-supply pipe network, the sensors are installed at some nodes selectively. Suppose in the problem discussed above, at the leakage pipeline section $E_5$, the sensor is only installed at $V_4$ and not installed at $V_6$. So, we need to determine the optimum upper end node sensor. We present a novel scheme to determine the locating sensor based on the incidence matrix.

In the directed graph G, $d^+(V)$ denotes the outdegree of vertex V, $d^-(V)$ denotes the indegree of vertex V and degree of vertex V can be expressed as:

$$d(V) = d^+(V) + d^-(V) \tag{11}$$

The incidence matrix of G is B (G) = ($b_{ij}$), so we get the outdegree, the indegree and the degree:

$$d^+(V_i) = \sum_{j=1}^{n} b_{ij} \tag{12}$$

$$d^-(V_i) = \sum_{j=1}^{n} b_{ji} \tag{13}$$

$$d(V_i) = \sum_{j=1}^{n} b_{ij} + \sum_{j=1}^{n} b_{ji} \tag{14}$$

The degree of each node in Fig. 2 is listed in Table 4. In the heat-supply pipe network, the degree of the node represents the number of the edge connecting to the node and the bigger the degree is, the bigger the attenuation or the interfere will be. To decrease the influence of the attenuation or interfere to the locating results, we propose to determine the locating sensor by assuring the summation of the degree of nodes be minimal, where those nodes pass from the upper end node sensor to the start node and the summation of the degree of nodes be minimal, where those node pass from the end node to the lower end node sensor, at the same time.

When leakage occurs at $E_5$, we obtain the serial number from $V_4$. The infrasound wave signal at $V_4$ can propagate to $V_1$, $V_2$, $V_3$, $V_5$ and sensor is installed only at, $V_3$, $V_5$. We calculate the summation of the degree of these nodes:

$$S_1 = d(V_1) + d(V_2) + d(V_4) = 1 + 3 + 3 = 7$$
$$S_3 = d(V_3) + d(V_2) + d(V_4) = 1 + 3 + 3 = 7$$
$$S_5 = d(V_4) + d(V_5) = 1 + 3 = 4$$

According to the above results, the summation of degree of the nodes from $V_4$ to $V_5$ is minimal, so we select the sensor at $V_5$ as the upper end sensor of leakage location.

## CONCLUSION

We establish the mathematical model of the pipe network and exploit the cosine of the intersection angle of the time difference vector to diagnose the pipeline. After assigning the elementary probability function, we merge the information according to the evidence and determine the leakage pipeline section. We calculate the summation of the degree of nodes at the start and the end of the pipeline to select the optimum sensor data to locate the leakage position. The experimental and theoretical results show that the proposed scheme can realize the decision of the leakage pipeline section accurately.

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