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Information Fusion Technology with Application to the Localization of Pipeline Leakage Based on Negative Pressure Wave Detection

[1]Er Li, [1]Yuehua Fan and [2]Xinde Li
[1]School of Environment Science and Engineering, Huazhong University of Science and Technology, China
[2]Department of Control Science and Engineering, Huazhong University of Science and Technology, China

Abstract: In this study, aiming to the problem of poor precision of localization or mistaken detection suffering from the influence of the noise and the burying status of observable spot through the negative pressure wave detection, especially, under the condition of leakage multi-source, we often find the phenomena of mistaken detection. To improve the precision and correctness of localization, we propose a kind of information fusion technology used to detect the leakage of water pipeline. Here firstly we adopted the clustering method of ISODATA (Iterative Self-Organization Data Analysis Techniques Algorithm) to classify the leakage multi-source and then give a more precise localization with the weighted average method to integrate the information from every leakage source. At last, an example is illustrated to testify the validity of this method.

Key words: Pipeline leakage, ISODATA, information fusion, localization, weighted average

INTRODUCTION

As we know that there is about 1.45 thousand millions cubes of water on the earth, however, there is little for individuals. Especially, treated water is distributed in the industrial world by means of pipeline networks. Leakage from the a water distribution pipeline network can be defined as that water which, having been obtained from a source, treated and put into supply, leaks or escapes other than by a deliberate action (Stephen *et al*., 2003). For example, in the UK, between 20 and 30% of transported water was lost through leakage during the 1990s (OFWAT, 2001). So all countries all over the world, especially, some developed countries put high premium on the management of supplying water and saving water. Earlier they carried out the research of the control of leakage and damage. There are also many organizations such as WRC in the UK, AWWA in American, JWWA in Japan. Many achievements have been made in the engineering. For example, the first relative leakage detection instrument was developed by WRC 1n 1960. British, American, French and Japanese have developed many practical and light-style detection instruments one after the other. Japanese and American also developed the geological radar in the mid of the 1980s, which can acquire the information of leakage by using wireless electric wave and reflect the status around the leakage with the display of image. At the beginning of the 1990s, they developed the relative detection instrument according to the principle of water noise to improve the reliability and correctness of instrument. German determined the location of leakage according to the intensity of leakage signals with pattern recognition.

Though leakage detection technology has made great progress, there are still many problems in localization, especially, with the development of intelligent detection system. In this study, aiming to the negative pressure wave detection technology, when we use it, there are all kinds of disturbance noise, measurement noise, besides the sound signal caused by leakage, which cause great uncertainty in detection and even sometimes bury the real detection signal and also give some virtual signals, so that it is easy to lead to mistaken detection and omitting detection.

Information fusion technology originated from the 1970s (Pan *et al*., 2003), which integrates information from multi-source by using math method and technology tool, in order to get useful information of high quality. In this paper, we solve the problem of leakage localization by applying information fusion technology.

PRINCIPLE OF THE NEGATIVE PRESSURE WAVE DETECTION

Negative pressure wave method avails itself of the principle of acoustic (Yuan *et al*., 2003). So-called pressure wave refers to the sound wave spending through the medium in the pipeline. When there is a leakage occurring in the pipeline, because of the pressure difference between inside and outside the pipe at the

Corresponding Author: Er Li, School of Environment Science and Engineering, Huazhong University of Science and Technology, China

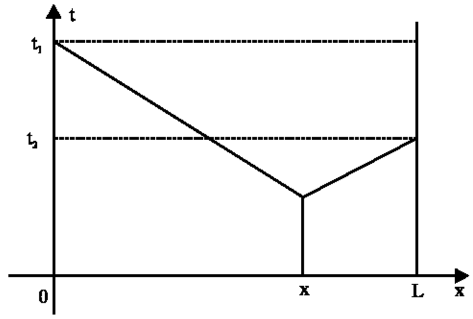

Fig.1: The principle of the negative pressure wave detection method

location of leakage, the liquid runs out of the pipe quickly, so that the pressure around the leakage decreases one after the other and then the neighboring liquid will flow towards the leakage, then the negative wave is produced. We compute the leakage location according to the spending speed of pressure wave and the time spent from the occurring location of negative pressure wave to two sensors. The principle of localization is shown in the Fig. 1.

A general localization equation of negative pressure wave detection is expressed as follows:

$$X = L+\alpha\ (t_1-t_2)/2 \quad (1)$$

where X is the distance between the leakage and the head end (m), L is the length of pipeline (m); α is the spending speed of negative pressure wave through the pipeline (m /S); t_1 is the time spent from the leakage to head end, t_2 is the time spent from the leakage to tail end. Generally speaking, α is the constant value, however, the speed of wave has some bearings on the density, pressure, specific heat of medium and structure, material, condition of burying, etc. Before localization, we must revise the speed of wave according to the characteristic parameters of pipeline. The formulation is given as follows:

$$\alpha = \sqrt{K(t)/\left(\rho(t)\left(1+\left(K(t)D/E\delta\right)\cdot\psi\right)\right)} \quad (2)$$

where K (t) is the function of liquid volume elasticity coefficient varied with temperature; ρ (t) is the function of density varied with temperature; D is the elasticity module of pipeline; D is the diameter of pipeline; δ is the thickness of pipeline; Ψ is the revised coefficient relative to the constraint condition of pipeline; μ is the Poisson coefficient; t is the temperature of liquid alongside the pipeline. Especially, for the thick pipeline of supplying water (i.e., $D/\delta<25$), because the distribution of stress in the pipe is uneven, the burying condition belongs to all - fixed style. Ψ coefficient is given as follows:

$$\Psi = 2\delta\ (1+\mu)/D+D\ (1+\mu^2)/(D+\delta) \quad (3)$$

For the pipeline of concrete, we may regard it as a thick pipeline the equation of speed of wave is given as follows:

$$\alpha = \sqrt{K(t)/\left(\rho(t)\left(1+\left(2K(t)(1+\mu)/E_R\right)\right)\right)} \quad (4)$$

where E_R is the grid module of pipeline material. When there is gas in the pipeline, due to the change of elasticity module, which has a distinct influence on the wave speed so the location equation of wave speed is revised as follows:

$$\alpha = \sqrt{\frac{K(t)}{\rho(t)\left[1+\left(2K(t)D\psi/E\delta+mK(t)RT/P^2\right)\right]}} \quad (5)$$

where m is the percent content of gas taken in the liquid; R is the constant value of gas; P is the absolute pressure intensity of liquid.

INFORMATION FUSION TECHNOLOGY

In recent years, with the rapid development of computer and network communication and the mutual promotion between them increasingly, the exigent need of C4I and IW system, information fusion technology has made great progress, of which application has been extended greatly from the martial to the civil. In this paper, aiming to the uncertainty of detection and localization of negative pressure wave, we propose a kind of information fusion technology based on ISODATA clustering method and weighted average method.

ISODATA clustering analysis: Because there might exist multiple sources of leakage between the two sensors, whether the detection is omitted rests on how to classify this information from multiple leakage sources. Here we adopt ISODATA method to classify them. Its idea is that during the course of iteration, readjust the categories and then compute the parameters inside the category and among the categories and compare them from the thresholds and then justify the action of union and division. Self-organization is going on by this way, in order to make every parameter satisfy the designing requirement and make the square sum of distance between each pattern and the center of categories become minimum.

Steps of algorithm are listed as follows

1. Set up parameters beforehand

- Set up the control parameter of clustering analysis:

c is the number of category beforehand;

N_c represents the number of the initial clustering (may be N_c is unequal to c);

θ_n is the minimum pattern number of every category (if less than the number, it won't become a category);

θ_s is the upper limitation of standard error of each component inside a category (split occurs when larger than the number)

θ_D is the lower limitation of distance between two categories. (if less than number and the two categories should be incorporated);

L is the maximum number of union in every iterative step.

I is the maximum iterative times.

- Put into the pattern characteristic vectors X_1, X_2,... X_N, which needs to be classified.
- Choose the initial center of clustering, we may choose N_c pattern characteristic vectors as the initial center z_j of clustering, from the set of pattern characteristic vectors to be classified, j = 1, 2, ..., N_c .

2. Assign each pattern in the pattern sets $\{x_i\}$ to some a category according to the principle of minimum distance, $d_{il} = \min_j \|x_i - z_j\|$ j = 1, 2, ...Nc, then $x_i \in \omega_1$ where d_{il} is the distance between x_i and the center z_j of ω_1 .
3. Judge the union according to θ_n, if the number n_j samples in the ω_j is less than θ_n and then cancel the center z_j of this category let $N_c = N_c-1$ go to step.
4. Compute the parameter after being classified as follows: the center of every category, the average distance inside a category and the average distance among all categories.

- Compute the center of every category

$$z_j = \frac{1}{n_j}\sum_{x_i\in\omega_j} x_i, j = 1, 2, \cdots, N_c \quad (6)$$

- Compute the average distance inside a category.

$$\bar{d}_j = \frac{1}{n_j}\sum_{x_i\in\omega_j} \|x_i - z_j\|, j = 1,2, ..., N_c \quad (7)$$

- Compute the total average distance between each pattern and its center of category.

$$\bar{d} = \frac{1}{N}\sum_{j=1}^{N_c} n_j \bar{d}_j \quad (8)$$

5. Judge the action "Stop, Spilt, incorporate " according to, I_p, N_C .

- if the iterative times I_p = 1 then let θ_D = 0 and go to step. otherwise, next.

- If $N_c \le c/2$ then go to step 6; Otherwise, next.
- If $N_c \ge 2c$ then go to step, Otherwise, next.
- If $c/2<N_c<2_c$ when the iterative times I_p is odd number, go to step 6.; Otherwise go to step.

6. Compute the vector of standard error inside a category

$$\sigma_j = (\sigma_{1j}, \sigma_{2j}, \sigma_{3j}, ... \sigma_{nj})\ j = 1,2, ... N_c$$

7. Find out the maximum component among the standard error.
8. In $\{\sigma_{j\ max}\}$ if some a $\sigma_{j\ max} > \theta_s$ at the same time, it satisfies the two condition as follows:

$$1)\ \bar{d}_j > \bar{d}_{nj} > 2\,(\theta_n+1)$$
$$2)\ N_c \le c/2.$$

then the category ω_j will be split into two clustering. The original z_j is cancelled and let $N_c = N_c+1$. We get two new centers of category z^+_j and z^-_j by adding and reducing $k\sigma_{jmax}$ in original component z_j, the other components won't change, here 0<k<1. k should make z^+_j and z^-_j in ω_j and the distance between the pattern of other category ω_j (I # j) and the new center is far, while the distance between the pattern of original category ω_j and the new center. After splitting $I_p = I_p+1$ go to step. otherwise, next.

9. Compute the distance between all categories and center

$$D_{ij} = \|z_i - z_j\|\ 1 = 1,2, ... N_c - 1\ j = i+1, ... N_c \quad (9)$$

10. Judge whether to incorporate according to θ_D and compare D_{ij} and θ_D, then arrange those D_{ij}, which is less than θ_D in incremental sequence, take the first L $D_{i_1 j_1} < D_{i_2 j_2} < ... D_{i_L j_L}$ incorporate the corresponding two classes at the beginning of D_{ij}. If the original two categories are z_i and z_j the new center after union is given as follows:

$$z_L = (n_i z_i + n_j z_j)/(n_i + n_j) \quad (10)$$

11. If the iterative times I_p = I or the process converges, then end. Otherwise, $I_p = I_p+1$. If need to adjust the parameter and go to step 1, otherwise, go to step 2.

Weighted average method: Though ISODATA clustering method can find out almost all sources of leakage, obviously, it can't supply the precise location. There are many methods and theories used to information fusion, i.e., Fuzzy theory, neural network, Rough theory, probability theory, DST (Shafer, 1976) and DSmT (Smarandache and Dezert, 2004), etc. Here we mainly integrate all samples in every category to give a precise location by using a sample weighted average method. Supposed that there are N_i measured values in the *i-th* source of leakage, which submit to normal school. Here we suppose that the probability p_{ij} that the *j-th* sample belongs to i-*th* source of leakage. The measured value of the j-*th* sample is x_j. Therefore we can get the new location of i-*th* source of leakage as follows:

$$\bar{x}_i = \sum_{j=1}^{N_i} p_{ij} x_j \Big/ \sum_{j=1}^{N_i} P_{ij} \tag{11}$$

AN NUMERICAL EXAMPLE

Supposed that the length of pipeline between two sensors is 120 m, the diameter size is 10 mm. There are 3 leakage sources on the pipeline, which are at 30, 60, 90 m. Supposed that there are 50 measured values (samples), which have been transformed to the distance as follows: {30,31,32,29,28,56,23,29,62,48,70,60,61,56,61,63,60,30,30,32,89,98,95,94,91,92,90,90,89,85,86,84,89,60,62,23,26,27,29,60,61,60,62,63,60,56,57,71,89,89}

We can get 3 categories by the ISODATA clustering analysis as follows:

Class 1: 30,31,32,29,28,23,29,30,30,32, 23,27,29;

Class 2:{56,62,48,70,60,61,56,61,63,60,60,62,60,61,60,62,63,60,56,57,71};

Class3: {89,98,95,95,94,91,92,90,90,89,85,86,84,89,89,89};

We can get the average value of every category as follows:

$$\bar{X}_1 = 28.69,\ \bar{X}_2 = 60.43,\ \bar{X}_3 = 90.31$$

here we let $\sigma \approx 3$ we can get the probability p_{ij} as follows:

Class 1: { 0.9091, 0.7435, 0.5441, 0.9947, 0.9739, 0.1655, 0.9947, 0.9091, 0.9091, 0.5441, 0.1655, 0.8533, 0.9947};

Class 2: {0.3361, 0.8720, 1.8715e-004, 0.0062, 0.9898, 0.9821, 0.3361, 0.9821, 0.6929, 0.9898, 0.9898, 0.8720, 0.9898, 0.9821, 0.9898, 0.8720, 0.6929, 0.9898, 0.3361, 0.5202, 0.0020};

Class 3: { 0.9091, 0.0374, 0.2946, 0.2946, 0.4693, 0.9739, 0.8533, 0.9947, 0.9947, 0.9091, 0.2088, 0.3563, 0.1095, 0.9091, 0.9091, 0.9091}

So we get the new location according to (11) as follows:

Class 1: New location after fusion: X_1=29.29; Real location X_1=30;

Class 2: New location after fusion: X_1=60.47; Real location X_2=60

Class 3: New location after fusion: X_3=90.03; Real location: X_3=90

It is obvious that we can get more precise location by comparing the result from the real one.

RESULTS

- By adopting ISODATA clustering method, here we get a higher precision of classification, a faster speed of convergence. If two locations are very near, we will adopt the ISODATA based on Fuzzy theory to improve the precision and correctness of classification.
- Seen from the result of fusion, it is well known that the precision of fusion is very high by comparing it from the real location according to a numerical example.
- This fusion technology not only gives a precise location for a single source, but also fits to the detection of multi-source leakage more.

CONCLUSIONS

In this study, we apply information fusion technology based on ISODATA clustering method and weighted average method to the detection and precise localization of pipeline leakage through negative pressure wave detection method. A precise location of single source is given by using it, but also a more advantage in localizing multi-source leakage precisely is found. Moreover, it avoids the shortcoming of imprecision of localization and mistaken detection of some past methods, fits to the online monitoring and control system of intelligent integration very much and is a very promising method.

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