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Application of wavelet-based EDA algorithm in detection and location of gas pipeline leak

Under complex conditions and background noise, gas pipeline leakage is difficult to pinpoint. This paper calculates with EDA based on wavelet analysis of Archimedes copula function, with location accuracy improved significantly. Acoustic emission signal of pipeline leakage not only has short delay, but also carries large amounts of physical information, thus with unique advantage in leak detection and location. According to pipeline detection and location principle of acoustic emission inspection and considering characteristics of city gas pipeline, improvement is proposed for location formula, appropriate wavelet basis and decomposition level plus threshold function are selected to conduct wavelet decomposition and reconstruction of analog experimental leak source signal. With modulus maxima method, more precise time difference of upstream and downstream acoustic signal is obtained. With it as a population sample to apply in EDA algorithm based on Archimedes copula function for optimization of population sample, the result shows that this method can accurately pinpoint gas pipeline leak source.

Key Words: Gas Pipeline; Acoustic Emission Location; Wavelet De-Noising; EDA; Optimization.

Introduction

With the rapid development of modern industry, gas pipeline scale is increasingly larger. But due to aging pipes, corrosion, abrasion and natural disasters and other unavoidable reasons, pipeline leak frequently occurs. Without timely detection and repair, significant casualties and property losses will likely be brought to the city public utilities, causing serious social environment pollution [1]. Therefore, the research to explore effective methods to timely detect pipeline leaks, discover small leaks in particular, and find the exact location of the leak, can not only end waste of energy and dissipation of poisonous and harmful materials, but also minimize accidents and reduce injuries and loss, which is significant for maintenance of urban public safety.

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Due to the small amount of leakage, for small pipeline leaks, leakage signal lasts short, imperceptible and with difficult hardware acquisition accuracy, often submerged in normal operating conditions and interference noise and difficult to identify and extract [2]. Moreover, city gas pipeline is usually with loop network, mostly low pressure pipe, with pressure, flow and other parameters varied as gas demand and gas scheduling changes. All these mean difficulty for detection and location of small leak of city gas pipeline.

Acoustic emission (abbreviated as AE), an excellent tool for detection and location of buried pipeline leak, does not require equipment to stop production or shorten downtime, its detection efficiency is especially high for small pipeline leak. Compared to other conventional methods such as tracer gas, infrared thermal imaging, ultrasound and electromagnetic scanning, it is more efficient [3]. Experiments also show that correlation-based approach is more accurate than other methods in determination of leakage signal. AE signals belongs to a non-stationary random signal essentially, while wavelet transform is an analytical method with good locality both in time and frequency domain, especially appropriate for non-stationary signal processing. AE signals with wavelet time and frequency domain analysis processing can provide valuable information. Taking advantage of the characteristic that signal and noise differ for wavelet transform coefficients at different scales, it separates noise from signal and thus achieves the purpose of de-noising, effectiveness of which has been demonstrated [4]. However, in practice, there are many interference noises in natural gas pipeline leak detection. Even wavelet transform is adopted for signal processing; there still is a big deviation in pipeline leak location accuracy. Based on wavelet noise cancellation analysis, this paper applies EDA algorithm based on Archimedean Copula function, builds population sample with the use of time difference of wavelet analysis, conduct approaching optimization of population sample to obtain optimal time difference, hereby obtaining a more accurate leak point location.

1. Leak location technology based on acoustic emission

1.1 Location Principle of Acoustic Emission Pipeline Leakage

When there is a pipeline leak somewhere, leak fluid shot forward at the leakage hole under pressure, and interacts with pipe wall, giving forth stress wave with certain frequency in the pipeline. The information stress wave with leak pipeline propagates to two ends along the pipe wall from the leak point. By installing sensors at both ends of leak point, stress wave signal can be collected for analysis. Suppose sensor A and B are placed at both ends of leak point, the leakage distance can be calculated with the following formula [5]:

... (1.1)

Wherein: x is the distance (m) from leak point to sensor A;

is the distance (m) between the two sensors;

v is propagation test speed (m/s) of stress wave;

is time difference (s) for the signals to propagate to two sensors.

1.2 Improved Wave Velocity and Location Calculation of Time Difference

When formula (1.1) is used for pipeline leak location, generally assume that leakage acoustic wave velocity is constant. Propagation velocity of actual pipeline leakage acoustic wave concerns a combination of factors such as pipe medium density, pressure, temperature, specific heat, etc. not a constant, which will bring greater location errors. In practical applications, velocity formula of natural gas pipeline leakage acoustic wave can be simplified as [6]:

... (1.2)

Wherein: α_p is gas compression coefficient (Pa-1);

ρ is gas density (kg/m^3);

is temperature (K);

p is intensity of pressure (105 Pa).

It can be known from formula (1.2) that wave propagation velocity inside the pipe varies as temperature and pressure change.

Formula [7] to calculate theoretical time difference for leakage acoustic wave to propagate to upstream and downstream sensor from leak point is as follows:

$$\Delta t = \int_0^x \frac{1}{v(x) - u(x)} dx - \int_x^L \frac{1}{v(x) + u(x)} dx \quad \text{... (1.3)}$$

As the city gas pipeline is generally low pressure pipeline, the impact of pipeline medium flow rate on acoustic velocity can be ignored, and then formula is thus simplified as:

$$\Delta t = \int_0^x \frac{1}{v(x)} dx - \int_x^L \frac{1}{v(x)} dx \quad \text{... (1.4)}$$

If formula (1.3) can accurately describe propagation of sound wave in city gas pipeline and transmission process of transmission medium in pipeline, then according to equation (1), (3) and (1.4), location of city gas pipeline leak points can be realized.

2 Wavelet and wavelet transform

Wavelet means a function or signal $\psi(x)$ in function space that satisfies the following condition:

$$C_\psi = \int_{R^+} \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty. \quad \text{... (2.1)}$$

In the formula, $R^* = R - \{0\}$ represents all non-zero real number, $\hat{\psi}(\omega)$ is Fourier transform of $\psi(x)$, which then becomes mother wavelet.

For real numbers , the parameter a is non-zero real numbers, the function [8]:

... (2.2)

Is referred to as continuous wavelet function generated by the mother wavelet $\psi(x)$ against parameters for , abbreviated as wavelet. Wherein, a is referred to as stretch factor; is referred to as shift factor.

$$x = \frac{L - v\Delta t}{2}$$

$$v(T,p) = \frac{1}{\sqrt{\alpha_p \rho(T,p)}}$$

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}} \psi\left(\frac{x-b}{a}\right)$$

The continuous wavelet transform of signal $f(x)$ can be defined as [9]:

$$W_f(a,b) = \frac{1}{\sqrt{|a|}} \int_R f(x) \psi\left(\frac{x-b}{a}\right) dx = \langle f(x), \psi_{a,b}(x) \rangle \quad \text{...2.3}$$

Wherein, inverse transform (reply signal or reconstructed signal) is as follows:

$$f(x) = \frac{1}{C_\psi} \iint_{R \times R^*} W_f(a,b) \psi\left(\frac{x-b}{a}\right) dadb \quad \text{... (2.4)}$$

Discrete wavelet transform of signal is defined as:

$$W_f(2^j, 2^j k) = 2^{-j/2} \int_{-\infty}^{+\infty} f(x) \psi(2^{-j} x - k) dx \quad \text{... (2.5)}$$

Its inverse transform (recovery signal or reconstructed signal) is as follows:

$$f(t) = C \sum_{j=-\infty}^{+\infty} \sum_{k=-\infty}^{+\infty} W_f(2^j, 2^j k) \psi_{(2^j, 2^j k)}(x) \quad \text{... (2.6)}$$

Wherein, C is a constant independent of the signal.

3. Estimation of distribution algorithms

Estimation of distribution algorithm (EDA), a typical stochastic optimization algorithm which combines traditional genetic algorithms and basic idea and advantages of statistical study, achieves optimal computation through the establishment of probability distribution model of the entire population [10]. EDA enjoys such advantages as strong adaption and self-learning ability, global search capability and fast convergence, and thus is now widely used in software testing, combinatorial optimization, process control, and many other fields. However, existing EDA either ignores the interconnectedness of variables, or has undesirable optimization effect, or takes a long time for model estimation. According to statistics, 90% of the time in EDA algorithm is spent on steps to estimate probability model. Therefore, for the sake of optimal operation result, this paper takes a new algorithm, i.e. EDA algorithm based on Archimedean Copula function, for precise location calculation.

3.1 Implementation Steps of Improved EDA Based on Archimedean Copula

(1) Population initialization randomly generates initial population Pop_t, which contains M individuals;

(2) Select, estimate individuals in population Pop_t, select N excellent individuals based on selection policy to constitute advantageous sub-cluster, wherein $N < M$;

(3) Establish probability model. First, estimate marginal distribution function $F_i(x)$, $i = 1, 2, ..., n$; of advantageous sub-cluster S_t; secondly, choose a suitable external generator ω_0, to build a suitable part to be nested with Archimedean Copula function C; based on $F_i(x)$, $i = 1, 2, ..., n$; and C obtained in the above two steps, construct probability distribution model of S_t [12];

(4) Sampling, conduct sampling of probability distribution model in (3) to form a new individual, and update the current population;

(5) Termination condition: Determine whether the algorithm termination condition is satisfied, if so, terminate, and otherwise go to (6);

(6) Leave the best k individuals in the population, and add to the next generation of population;

(7) Variation: Select r outstanding individuals in the current population for variation before added to the next generation of population.

(8) Loop iteration, order $t \leftarrow t + 1$, go to (2).

The above EDA algorithm based on Archimedes addresses shortcomings of EDA in long optimization time and complicated probability model, with the specific flow chart shown in Fig.1.

3.2 Experimental Data Simulation

Pipeline in simulation experiment is straight pipe of 5000mm long with pipe diameter of 32.9mm. The pipeline medium is air and pipeline pressure (gauge pressure) is 0.2MPa. Simulated leakage hole is at 3600mm of the pipeline. In order to simulate different leakage rate, pipeline leakage rate is respectively controlled at 1.0%, 2.0% and 3.0% of the total flow to conduct three groups of experiments under three circumstances, with three times per group and 9 experimental data is collected.

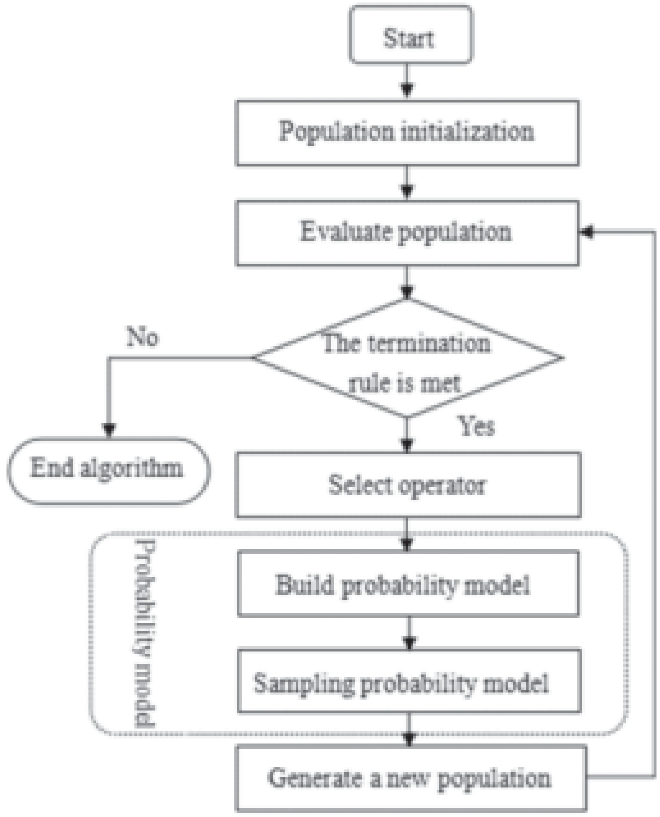

Fig.1 Flow chart of EDA based on archimedes

Make calculation of the above collected experimental data according to formula (1.1), (1.2) and (1.4) of section 1 in this paper, conduct error analysis, and location result statistics is shown in Table 1.

4. Multistage wavelet denoising location based on matlab wavelet toolbox

4.1 Data Processing for Pipeline Leak

4.1.1 Wavelet basis and scale determination

Acoustic emission signals are often accompanied by other signals, such as signal generated by the natural frequency of the pipe, background noise and so on. Selection of appropriate wavelet and wavelet basis will cause a significant impact on accuracy of pipeline leakage signal. The papers first compare SNR and MSE and then obtain optimal wavelet and wavelet basis.

Definition of SNR [13]:

$$SNR = 10 \times \log_{10} \frac{E_s}{E_n} \qquad ... (4.1)$$

TABLE 1 LEAK LOCATION STATISTICAL ANALYSIS IN SIMULATION ANALYSIS

Leakage rate	Actual leak point (mm)	Location value 1 (mm)	Location value 2 (mm)	Location value 3 (mm)	Mean (mm)	Error
1.0%	3600	3617	4206	3243	3689	2.5%
2.0%		3175	3071	3070	3105	13.75%
3.0%		2893	2895	2897	2895	19.6%
Average error				11.95%		

In the formula, and denote signal power and noise power respectively, which can be obtained through calculation of sum of square of the sampling point.

Definition of MSE [14]:

$$SNR = \frac{1}{n}\sum_{i=1}^{n}\{F(i) - R(i)\}^2 \quad \text{... (4.2)}$$

In the formula, n represents sampling point; F and R represent signal before and after processing respectively. The smaller MSE has made the better signal processing effect.

In order to select the optimal wavelet, we decompose collected leakage signal under the same scale based on different wavelets in experiment, compare SNR and MSE of the signal after decomposition, and the results are shown in Table 2.

TABLE 2 MSE AND SNR OF DIFFERENT WAVELET BASES

Wavelet basis function	SNR	MSE (10-4)
Db1	35.8263	3.4456
Db3	35.8672	3.5523
Db6	35.8977	3.4478
Coif4	35.2563	3.5619
Sym2	35.1346	3.5676

By comparison, for signal after db6 decomposition, SNR reaches maximum, SME reaches minimum, better than the remaining 4 wavelet analysis. Therefore, db6 is chosen as wavelet basis for noise cancellation.

By multi-scale analysis of acoustic emission signal under the same wavelet basis, optimal scale can be obtained. Conduct 6-scale decomposition of leakage analog signal with db6. According to selection basis of wavelet basis scale, 4-scale is optimal.

4.1.2 Selection of threshold value

For selection of threshold value, heuristic threshold selection (heursure) is taken as threshold selection rule [15, 16]. There are two threshold approaches: hard thresholding and soft thresholding. Hard thresholding will break at some point, while soft thresholding can effectively avoid signal interrupt, so that reconstructed signal is smoother. Also compared to hard thresholding, soft thresholding has higher SNR and smaller SME. The two thresholding results have shown in Table 3.

TABLE 3 SNR AND S SME UNDER HARD AND SOFT THRESHOLDING

Project	Hard thresholding	Soft thresholding
SNR	35.8643	35.8965
MSE (10-4)	3.4423	3.4218

Therefore, soft thresholding is adopted for the study.

4.2 RESULT ANALYSIS OF MATLAB WAVELET DE-NOISING

As illustrated above, conduct 4-scale analysis of leakage signals with db6, take soft threshold selection method of heuristic threshold; carry out wavelet de-noising processing of three groups of signal respectively with 1.0%, 2.0%, and 3.0% of leakage amount. Wherein, de-noising results of upstream and downstream leakage signal for leakage amount of 1.0% are shown in Fig.2 and 3.

Carry out singularity analysis of the signal. Singularity of upstream sensor is at about 600 points of sampling points, while singularity of downstream sensor is at about 282 points of sampling points. Sampling point difference is thus 418, and time difference after calculation is 438×10-6s.

Conduct de-noising processing for the other two groups of leakage signal respectively with the same procedure, obtaining time difference after wavelet noise cancellation as shown in Table 4 and Table 5.

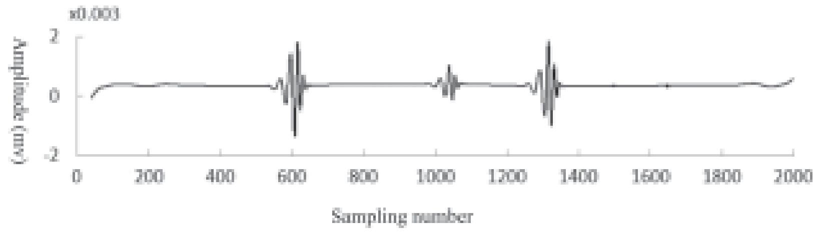

Fig.2 Noise cancellation of upstream sensor

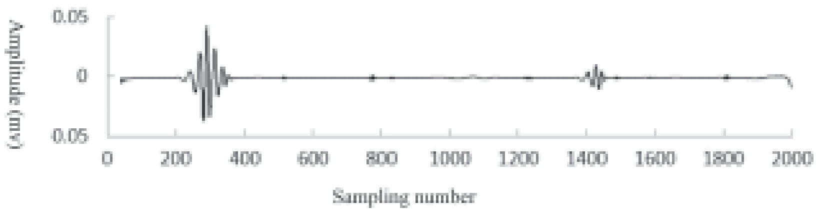

Fig.3 Noise cancellation of downstream sensor

TABLE 4 SINGULARITY TIME DIFFERENCE CALCULATION OF LEAKAGE SIGNAL WITH 2.0% LEAKAGE AMOUNT AFTER NOISE CANCELLATION

	Sampling number	Sampling number difference	Time difference(s) of upstream and downstream sensor
Upstream signal	1400	480	480×10-6
Downstream signal	1880		

Convert into coordinates in AE software, i.e. of leak location.

TABLE 5 SINGULARITY TIME DIFFERENCE CALCULATION OF LEAKAGE SIGNAL WITH 3.0% LEAKAGE AMOUNT AFTER NOISE CANCELLATION

	Sampling number	Sampling number difference	Time difference(s) of upstream and downstream sensor
Upstream signal	1700	300	300×10-6
Downstream signal	2000		

Convert into coordinates in AE software, i.e. of leak location.

Through correlation location analysis of three groups of experimental data after wavelet noise cancellation, three groups of average error is 7.6% (Table 6). Comparison of data before and after wavelet denoising reveals that location accuracy is improved to some extent after wavelet denoising, but the error is still large.

5 EDA Algorithms for time difference optimization

Accuracy of time difference determines location accuracy. Average error in Table 6 constitutes time difference after a wavelet analysis processing, which is with larger resulting location error on the one hand and not universal on the other hand. Thus, EDA algorithm is adopted for population optimization of wavelet analysis, obtain optimal time difference and then conduct location calculation. For wavelet analysis, sampling frequency is 10 to 20 times of the highest frequency of the filter. By changing the sampling rate, 40 groups of time difference can be obtained as population sample (Table 7). Select the objective function and fitness function; construct EDA through Matlab toolbox programming algorithm, with steps as follows:

(1) Take time difference obtained after wavelet analysis as the initial population $X = (X_1, ..., X_n)$, population quantity is N=40, and maximum number of iterations is G=1000 times;

(2) Objective function: Select the mean function

$$G(x) = \frac{\sum_{i=1}^{n} X_i}{n};$$

(3) The fitness function $f(x) = \frac{1}{1-g(x)}$.

TABLE 7 TIME DIFFERENCE SAMPLE OF WAVELET ANALYSIS FOR EDA ALGORITHM

Data number	Time difference (10-6 s)				
1-5	318	380	100	320	295
6-10	276	343	342	265	274
11-15	263	285	390	420	470
16-20	190	250	270	310	360
21-25	270	320	239	410	450
26-30	160	350	460	410	430
31-35	485	390	420	450	440
35-40	360	370	460	410	450

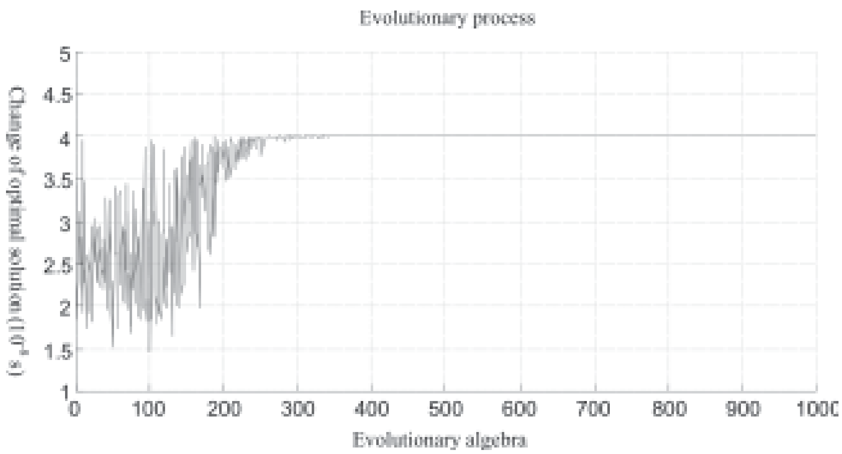

Fig.4 Evolutionary process of EDA algorithm

TABLE 6 GAS PIPELINE LEAK LOCATION STATISTICS AFTER WAVELET DENOISING

Leakage rate	Actual leak point (mm)	Location value 1 (mm)	Location value 2 (mm)	Location value 3 (mm)	Mean (mm)	Error
1.0%	3600	3973	4066	3515	3851	6.9%
2.0%		3661	3916	3996	3858	7.2%
3.0%		3780	4170	3787	3912	8.6%
Average error			7.6%			

TABLE 8 ANALYSIS AND COMPARISON OF EDA ALGORITHM FOR ACCURATE LOCATION CALCULATION

Leakage rate	Actual leak point (mm)	Acoustic emission location (mm)	Wavelet denoising location (mm)	EDA algorithm location (mm)
1.0%	3600	3689	3851	3750
2.0%		3105	3858	3750
3.0%		2895	3912	3750
Average value	3600	3230	3874	3750
Average error		11.95%	7.6%	4.1%

With the above time difference as the initial sample, simulate with EDA algorithm based on Archimedes copula function as described in section III of this paper and obtain evolutionary process of EDA algorithm, as shown in Fig.4. It can be known from the figure that after 300 times, number of iterations tends to stabilize, and optimal solution of time difference is 4×10-8 s. Substitute in formula (1.1), (1.2), (1.4) in section 1, calculate and obtain that location of leak point is at 3750 mm.

Conduct location analysis of average value of 3 location values in Tables 1 and 6, and obtain location result comparison as shown in Table 8 form where, it can be seen that direct detection location through acoustic emission detector is with high error rate which reaches 11.95%. After wavelet de-noising processing and combination of improved correlation location calculation, obtained error rate is reduced, but still relatively large. Simulate with EDA algorithm based on Archimedean copula function, conduct population optimization of obtained multiple time difference and then obtain optimal time difference, with final error rate dropped to 4.1% and location accuracy improved greatly.

6. Conclusions

Acoustic emission hardware location, wavelet analysis location, EDA algorithm and comparative analysis of wavelet analysis location, reach the following conclusions:

(1) Acoustic emission signal of pipeline leakage not only has short delay, but also carries large amounts of physical information, thus with advantage in pipeline leak detection and location. With urban gas pipeline running characteristics, improvement is made in velocity and time difference of traditional detection and location formula of acoustic emission, to make it more in line with the actual city pipeline. On this basis, with wavelet transform denoising, identify time difference of upstream and downstream leakage signal to obtain more accurate location data of leak source which verifies the feasibility of the method.

(2) By selecting the objective function and fitness function, structure EDA algorithm based on Archimedean copula function, conduct evolutionary computation of population time difference sample after wavelet denoising processing, obtain the optimal time difference and thus location value of leak point. Compared to wavelet denoising analysis, EDA algorithm can obtain more accurate results, which greatly improves location accuracy and can be extended to practical engineering applications.

(3) Since simulation experiment eliminates ambient noise and other factors, the location results are more accurate. Surrounding working conditions and noise interferences should be considered in practical applications. Also, sample number needs to be considered during application of EDA algorithm.

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